

**An Integrated Thermal Simulation & Generative Design
Decision Support Framework for the Refurbishment or
Replacement of Buildings: A Life Cycle Performance
Optimisation Approach**

- Yair Schwartz -

**The Bartlett School of Environment, Energy and Resources
University College London**

**This thesis is submitted in partial fulfilment
of the requirements for the degree of Doctor
of Engineering (EngD)**

2018

Student Declaration

I, Yair Schwartz, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Signature:

Abstract

The environmental performance of existing buildings can have a major role in achieving the CO₂ reduction targets, set out by the UK government. In the UK, new buildings account for around 1% of the total building stock (annually), and predictions show that around 75% of the housing stock that will still remain in 2050 has already been built. Furthermore, while current building performance improvement efforts focus mainly on the operational performance of buildings, the environmental impact of the built environment is the result of processes that occur throughout their whole life-cycle (construction, usage and demolition).

To achieve significant CO₂ emission reductions in the built environment in an economically viable way, this thesis adopted the Life Cycle Carbon Footprint (LCCF) and Life Cycle Cost (LCC) analysis approaches, to enable a cross-comparison between multiple design alternatives and to identify the preferable design solution: the refurbishment of existing buildings or their replacement by new ones. In particular, this thesis has developed, tested and validated a computational framework that integrates life cycle performance protocols (EN 15978:2011 and BS ISO 15686-5), thermal simulation tools (EnergyPlus), mathematical optimisation (NSGA-II) and a designated building generative design programming (PLOOTO - Parametric Lay-Out Organisation generator) into a single computer application.

The investigation was carried out using a comparative analysis of simulated case study buildings: a terrace-house, a bungalow and a block of flats. Results show that under the considered assumptions, the optimal refurbishment case studies achieved lower LCCF and LCC values than the replacements: The LCCF of the refurbishment scenarios was between 1,100-1,500 kgCO_{2e}/m² and their LCC 440-680 £/m², compared to those of the replacements scenarios, who achieved between 1,220-1,850 kgCO_{2e}/m² and 550-890 £/m².

Furthermore, this research has found that optimising the performance of a typical London-based terrace house using a life cycle carbon approach reached 10% more savings in CO₂ throughout its life, compared to targeting operational CO₂ only. This means that complying with current UK regulations – which is currently only focused on the improvement of operational efficiencies – may result in buildings with poorer performance, in terms of their overall life cycle carbon footprint. This is associated to the difference in the analysis scope: while operational efficiencies only examine emissions due to heating and lighting within the building, the Life Cycle approach accounts for emissions that occur in other stages in the building's life, e.g., emissions that are embodied within its structure, emissions during construction, maintenance and more.

An important conclusion of this research is, therefore, that to reach significant reductions in emissions rates – a life-cycle approach should be adopted. More specifically, to achieve immediate reductions (on a 20-year scale) - refurbishments are generally preferable over replacements. It can, therefore, be concluded that there is a greater importance in incentivising re-use to achieve quicker emissions reductions.

The research has shown that the integration of the various research tools in the proposed computational framework was successful in automating the analysis process. The comparative analysis approach was found to be useful in identifying the preferable design solution – the refurbishment of existing buildings or their replacement. Finally, the research sets out an extensive discussion in regard to the proposed computational framework, life cycle performance analysis and the potential benefits of refurbishments or replacements of existing buildings, in the context of the UK.

ACKNOWLEDGEMENTS

This study was delivered and funded jointly by the Engineering and Physical Sciences Research Council (EPSRC), the UCL EngD VEIV (Virtual Environments, Imaging and Visualisation) program and Hawkins Brown LLP Architectural practice.

I owe my deepest gratitude to my supervisors, Professor Dejan Mumovic and Dr. Rokia Raslan (Bartlett School of Environment, Energy and Resources) for their invaluable support and assistance throughout the years, and to my industrial supervisor, Louisa Bowels (Hawkins Brown), for her expert guidance and support.

I would also like to thank to Dr. Ivan Korolija, for his assistance throughout, and particularly for providing technical support in running Legion - UCL's high-performance computing services.

My gratitude also goes to my UCL colleagues, and especially Chris van Dronkelaar and Stathis Eleftheriadis, my partners in this journey, for keeping our spirits up.

Lastly, I will always be thankful to my family, and especially my parents, for their endless and priceless support. Special thanks go to my wife, Elite, and our son, Jonathan, from whom I have learned most.

לאבא,

Table of Contents

1. Introduction.....	19
1.1. Context.....	19
1.2. Research Scope.....	20
1.2.1. Research Aims and Objectives	20
1.2.2. Research Approach Summary	22
1.2.3. Research Tools and Techniques	23
1.3. Contribution	24
1.3.1. Contribution to Knowledge and List of Papers.....	24
1.3.2. Impact Statement - Contribution to Industry.....	26
1.4. VEIV (Virtual Environments, Imaging and Visualisation) - Industrial Sponsor: Hawkins Brown LLP	28
1.5. Thesis Structure.....	29
2. Literature Review	32
2.1. To Refurbish or to Replace – Review of Evidence	32
2.1.1. Evidence in Support of Replacement.....	34
2.1.2. Evidence in Support of Refurbishment.....	34
2.1.3. Ambiguous Results.....	35
2.1.4. ‘Refurbish or Demolish’ in The UK Context	36
2.2. Life Cycle as Performance Metric in the Built Environment	39
2.2.1. Background	39
2.2.2. Resource Flows in Buildings	39
2.2.3. The Life Cycle Assessment (LCA) Framework.....	41
2.2.4. Life Cycle Carbon Footprint (LCCF) and EN 15978:2011	43
2.2.5. Life Cycle Cost (LCC) and BS ISO 15686-5.....	47
2.2.6. Limitations of Life Cycle Studies.....	50
2.3. Life Cycle Carbon Footprint (LCCF) of New and Refurbished Buildings.....	52
2.3.1. Context	53
2.3.2. Limitations and Uncertainties.....	55
2.3.3. Findings	57
2.4. Computational Analysis Techniques	61
2.4.1. Parametric Modelling.....	61
2.4.2. Generative Spatial Design Programming.....	65
2.5. The Application of Computational Techniques in the Built Environment.....	69
2.5.1. The use of Optimisation Algorithms	69

2.5.2.	The Application of Optimisation in the Built Environment.....	73
2.5.3.	Coupling Optimisation Algorithms and Generative Design	77
2.5.4.	Summary	79
2.6.	The Knowledge Gap.....	80
3.	Methodology	84
3.1.	Research Design – the Development of a Computational Framework.....	85
3.1.1.	Framework Component 1 - Optimising the Refurbishment of a Case Study Building	87
3.1.2.	Framework Component 2 – The Generation of Optimal New Designs using PLOOTO - Parametric Lay-Out Organisation generaTOr	87
3.1.3.	Framework Component 3 – The Validation of a Life Cycle Performance GA Optimisation Application.....	88
3.2.	Methods and Tools.....	88
3.2.1.	Comparative Case Study Analysis	88
3.2.2.	Modelling and Simulation	90
3.3.	Implementation.....	91
3.4.	Testing, Validation and Verification	97
3.4.1.	Study Design Validation	97
3.4.2.	Data Input Validation	98
3.4.3.	Optimisation Validation and Verification	99
3.4.4.	Generative Design.....	99
4.	The Development, Testing and Validation of the Proposed Computational Framework	101
4.1.	Framework Component 1: Exploring the Potential of Optimising the Refurbishment of a Case Study Building.....	102
4.1.1.	Aim.....	102
4.1.2.	The Case Study Building	102
4.1.3.	Methodology and Study Design	104
4.1.4.	Study Assumptions	105
4.1.5.	Results and Discussion	107
4.1.6.	Findings Summary	110
4.2.	Framework Component 2: Coupling Building Performance Optimisation and PLOOTO as Generative Spatial Design Application.....	111
4.2.1.	Aim.....	111
4.2.2.	Methodology and Study Design	112
4.2.3.	Results and Discussion	113
4.2.4.	Findings Summary	118

4.3.	Framework Component 3: The validation of the Designated Parametric Controller and NAGA-II Optimisation Tool	119
4.3.1.	Aim.....	119
4.3.2.	Methodology and Study Design	119
4.3.3.	Results and Discussion	122
4.3.4.	Findings summary.....	124
4.4.	Developing the Computational Framework - Summary	125
5.	Implementation of the Proposed Framework.....	127
5.1.	Research Implementation.....	127
5.1.1.	Analysis Structure	127
5.1.2.	Pareto-edge Models	129
5.1.3.	Goal and Scope	130
5.1.4.	Life Cycle Impact Assessment.....	131
5.1.5.	Life cycle Inventory.....	132
5.2.	Case Study 1 – Terrace house.....	139
5.2.1.	The Case Study Building	139
5.2.2.	Design Scenarios	139
5.2.3.	Optimisation Results and Pareto Fronts	141
5.2.4.	Pareto Models Analysis	144
5.2.5.	Aggregated Year-By-Year Overall Emissions and Costs	146
5.2.6.	Life Cycle Stages Comparison	148
5.2.7.	Embodied and Recurrent CO ₂ and Cost Breakdown	151
5.3.	Case Study 2 – Bungalow.....	152
5.3.1.	The Case Study Building	152
5.3.2.	Design Scenarios	152
5.3.3.	Optimisation Results and Pareto Fronts	154
5.3.4.	Pareto Models Analysis	156
5.3.5.	Aggregated Year-By-Year Overall Emissions and Costs	158
5.3.6.	Life Cycle Breakdown Comparison	160
5.3.7.	Embodied and Recurrent CO ₂ and Cost Breakdown	162
5.4.	Case Study 3 – Block of Flats.....	164
5.4.1.	The Case Study Building	164
5.4.2.	Design Scenarios	164
5.4.3.	Optimisation Results and Pareto Fronts	167
5.4.4.	Pareto Models Analysis	169

5.4.5.	Aggregated Year-By-Year Overall Emissions and Costs	171
5.4.6.	Life Cycle Breakdown Comparison	173
5.4.7.	Embodied and Recurrent CO ₂ and Cost Breakdown	175
6.	Discussion.....	178
6.1.	The Implementation of the Computational Framework	178
6.1.1.	Operational Use Optimisation vs. Life Cycle Performance Optimisation	178
6.1.2.	Refurbish or Replace? - Operational vs. Life-Cycle Performance Optimisations.....	181
6.1.3.	Life Cycle Performance Excluding the Demolition of Existing Building ..	182
6.1.4.	Limitations of Comparative Studies	184
6.2.	Life Cycle Analysis Protocols	186
6.2.1.	Life Cycle Analysis Protocol Assumptions and Limitations	186
6.2.2.	The LCC Calculation Method	190
6.2.3.	Life Cycle Performance Normalisation	193
6.3.	Analysis of the Case Studies - Findings summary	195
6.4.	Future Developments in the Optimisation of Buildings for Life Cycle Performance.....	200
6.4.1.	Dynamic Embodied CO ₂ Databases	200
6.4.2.	Coupling BIM and Embodied CO ₂ Evaluation and Life Cycle Analysis.....	201
6.4.3.	Energy Consumption: Minimising the Impact of the Performance Gap...	202
6.4.4.	Computing and Processing Time.....	202
6.4.5.	Generative Design.....	203
7.	Conclusions and Future Work.....	207
7.1.	Conclusions and Contribution to Knowledge	207
7.1.1.	Establishing the Computational Framework for LCCF and LCC optimisation	207
7.1.2.	Life Cycle Protocols.....	209
7.1.3.	Refurbishments and Replacements in the UK context.....	210
7.2.	Future Work	212
8.	References.....	215
	Appendix A – Building Components and Materials Data.....	235
	Appendix B – EPD Sources.....	237
	Appendix C – Refurbishment Scenarios – Build-ups and Building Components ..	238
	Appendix D – Replacement Scenarios – Build-ups and Building Components	240
	Appendix E – Thermal Zones and Schedules	243
	Appendix F – LCCF and LCC Assumptions	256

List of Figures

Chapter 1

<i>Figure 1.1: The thesis structure and list of chapters</i>	29
--	----

Chapter 2

<i>Figure 2.1: The UK Housing Stock. BRE unpublished research</i>	37
<i>Figure 2.2: Input and output Energy flows in buildings</i>	41
<i>Figure 2.3: The LCA Framework</i>	43
<i>Figure 2.4: Building life cycle, according to EN 15978:2011</i>	43
<i>Figure 2.5: Life Cycle Cost (LCC) as part of Whole Life Costing (WLC)</i>	49
<i>Figure 2.6: LCCF results for 60 years, all case studies.</i>	58
<i>Figure 2.7: The relationship between LCCF and LCE</i>	58
<i>Figure 2.8: New/Refurbished buildings – all buildings types LCCF (kgCO₂/m²) for 50 years.</i>	60
<i>Figure 2.9: UK and Ireland- New / Refurbished buildings LCCF (kgCO₂/m²) for 50 years</i>	60
<i>Figure 2.10. The Travelling Salesman Problem – a parametric combinatorial problem example</i>	61
<i>Figure 2.11: Pareto front</i>	62
<i>Figure 2.12: Multidimensional search space with global and local optimums</i>	63
<i>Figure 2.13: The step-by-step execution of Genetic Algorithms optimisation</i>	65
<i>Figure 2.14: Contour manipulation</i>	66
<i>Figure 2.15: Shape grammar and sub-division of pre-defines spaces</i>	66
<i>Figure 2.16: The basic starting-point layout in Caldas (2001), and some of its parametric variations</i>	67
<i>Figure 2.17: The use of thermal simulation tools in building optimisation studies</i>	74
<i>Figure 2.18: Multi-objective 'bottom-up' shape optimisation approach – Energy consumption and Lighting loads</i>	78

Chapter 3

<i>Figure 3.1: Research flow – the development, validation and implementation of the computational framework</i>	85
<i>Figure 3.2: Research design - The proposed computational framework</i>	86
<i>Figure 3.3: Various spatial arrangements based on a single distribution of points.</i>	94
<i>Figure 3.4: The steps of a Parametric Thermal Simulation</i>	95

Chapter 4

<i>Figure 4.1: The research design and the components examined by the pilot studies</i>	101
<i>Figure 4.2: Park Hill site plan</i>	103

<i>Figure 4.3 Park Hill after construction</i>	103
<i>Figure 4.4: Pilot study 1 – study design</i>	104
<i>Figure 4.5: Pilot study execution sequence</i>	105
<i>Figure 4.6: Building "B" (left) and the elements for the GA optimisation (right)</i>	106
<i>Figure 4.7: Optimisation results – Finding pareto-optimal solutions for the different buildings</i>	108
<i>Figure 4.8: Comparison of non-refurbished, refurbished and optimal building options: 60-year operational-energy related CO2 emissions.</i>	109
<i>Figure 4.9: Non-refurbished, refurbished and optimal buildings – 60 years LCCF</i>	109
<i>Figure 4.10: Fully south-facing building. (a): LCCF/LCC: Natural Gas Heating. (b): Annual heating energy consumption/Annual spending (Building B)</i>	110
<i>Figure 4.11: The steps of a parametric thermal simulation optimisation</i>	113
<i>Figure 4.12: Pilot study 2 - study design</i>	113
<i>Figure 4.13: The dimensions of the three rooms (left). The four possible spatial arrangements (right)</i>	114
<i>Figure 4.14: a 'typical' London terrace house</i>	115
<i>Figure 4.15: The 15 building geometries generated by PLOOTO.</i>	116
<i>Figure 4.16 Left - Pareto-optimal front of 3 optimal models. Right - The performance of the best and worst models</i>	117
<i>Figure 4.17: Best and worst performing geometries</i>	117
<i>Figure 4.18: Pilot study 3 - study design</i>	118
<i>Figure 4.19: Execution - 3rd pilot study</i>	122
<i>Figure 4.20: The LCCF and LCC results of the entire search space</i>	123
<i>Figure 4.21: The LCCF and LCC of 600 random (Monte Carlo) models, laid over the entire search space (top), and the LCCF and LCC of 600 (10 generations, 60 models) NSGA-II models, laid over the entire search space (bottom)</i>	123
<i>Figure 4.22: The LCCF and LCC of 300 random (Monte Carlo) models, laid over the entire search space (top), and the LCCF and LCC of 300 (10 generations, 300 models) NSGA-II models, laid over the entire search space (bottom)</i>	124

Chapter 5

<i>Figure 5.1: Study implementation</i>	127
<i>Figure 5.2: Pareto front (light gray) and Pareto edge models</i>	129
<i>Figure 5.3: Terrace house and its exposed surfaces</i>	133
<i>Figure 5.4: Bungalow and its exposed surfaces</i>	133
<i>Figure 5.5: Block of flats and its exposed surfaces</i>	134
<i>Figure 5.6: Refurbishment scenarios alternative build-ups</i>	137
<i>Figure 5.7: Replacement scenarios alternative build-ups</i>	138
<i>Figure 5.8: Case study 1 - A 'typical' London terrace house</i>	139

<i>Figure 5.9: Case study 1 – Thermal zones and potential windows orientation for the optimisation of the terrace house refurbishment</i>	140
<i>Figure 5.10: PLOOTO outputs – the 32 new-build terrace house designs</i>	141
<i>Figure 5.11: Terrace house refurbishment results – LCCF/LCC for 60 years, pareto front and GA convergence</i>	142
<i>Figure 5.12: Terrace house replacement results – LCCF/LCC for 60 years, pareto front and GA convergence</i>	143
<i>Figure 5.13: Refurbishment vs Replacement: Pareto models comparison</i>	144
<i>Figure 5.14: The properties of the pareto-front models of a terrace house refurbishment</i>	145
<i>Figure 5.15: The properties of the pareto-front models of a terrace house replacement</i>	145
<i>Figure 5.16: Best terrace replacement floor plans, elevations and thermal zones</i>	146
<i>Figure 5.17: Terrace house - Aggregated annual refurbishments and replacements emissions</i>	147
<i>Figure 5.18: Terrace house - Aggregated annual refurbishments and replacements costs</i>	148
<i>Figure 5.19: Terrace house refurbishment and replacements life cycle CO₂ stages breakdown</i>	149
<i>Figure 5.20: Terrace house refurbishment and replacements life cycle cost stages breakdown</i>	149
<i>Figure 5.21: Refurbishment vs Replacement: life cycle performance breakdown</i>	150
<i>Figure 5.22: Terrace house embodied CO₂ breakdown (stages A+B4)</i>	151
<i>Figure 5.23: Terrace house embodied cost breakdown (stages A+B4)</i>	151
<i>Figure 5.24: Case study 2 - A 'typical' London bungalow house</i>	152
<i>Figure 5.25: Case study 2 – Thermal zones and potential windows orientation for the optimisation of the bungalow refurbishment</i>	153
<i>Figure 5.26: PLOOTO outputs – the 50 new-build bungalow designs</i>	154
<i>Figure 5.27: Bungalow refurbishment results – LCCF/LCC for 60 years, pareto front and GA convergence</i>	155
<i>Figure 5.28: Bungalow replacement results – LCCF/LCC for 60 years, pareto front and GA convergence</i>	155
<i>Figure 5.29: Refurbishment vs Replacement: Pareto models comparison</i>	156
<i>Figure 5.30: The properties of the pareto-front models of a bungalow house refurbishment</i>	156
<i>Figure 5.31: The properties of the pareto-front models of a bungalow house replacement</i>	157
<i>Figure 5.32: Best bungalow replacement floor plan, elevations and thermal zones</i>	158
<i>Figure 5.33: Bungalow - Aggregated annual refurbishments and replacements emissions</i>	159
<i>Figure 5.34: Bungalow - Aggregated annual refurbishments and replacements costs</i>	159
<i>Figure 5.35: Bungalow refurbishment and replacements life cycle CO₂ stages breakdown</i>	160
<i>Figure 5.36: Terrace house refurbishment and replacements life cycle cost stages breakdown</i>	161
<i>Figure 5.37: Refurbishment vs Replacement: life cycle performance breakdown</i>	162
<i>Figure 5.38: Bungalow embodied CO₂ breakdown (stages A+B4)</i>	163
<i>Figure 5.39: Bungalow embodied cost breakdown (stages A+B4)</i>	163
<i>Figure 5.40 Case study 3 - A 'typical' London block of flats</i>	164

<i>Figure 5.41 Case study 2 – Thermal zones and potential windows orientation for the optimisation of the block of flats refurbishment</i>	165
<i>Figure 5.42: PLOOTO outputs – the 27 new-build designs</i>	167
<i>Figure 5.43: Block of flats refurbishment results – LCCF/LCC for 60 years, pareto front and GA convergence</i>	168
<i>Figure 5.44: Block of flats replacement results – LCCF/LCC for 60 years, pareto front and GA convergence</i>	168
<i>Figure 5.45: Refurbishment vs Replacement: Pareto models comparison</i>	169
<i>Figure 5.46: The properties of the pareto-front models of a block of flats refurbishment</i>	169
<i>Figure 5.47: The properties of the pareto-front models of a block of flats replacement</i>	170
<i>Figure 5.48: Best flats replacement floor plan, elevations and thermal zones</i>	171
<i>Figure 5.49: Block-of-flats - Aggregated annual refurbishments and replacements emissions</i>	172
<i>Figure 5.50: Block-of-flats - Aggregated annual refurbishments and replacements costs</i>	173
<i>Figure 5.51: Block-of-flats refurbishment and replacements life cycle CO₂ stages breakdown</i>	174
<i>Figure 5.52: Block-of-flats refurbishment and replacements life cycle cost stages breakdown</i>	174
<i>Figure 5.53: Refurbishment vs Replacement: life cycle performance breakdown</i>	175
<i>Figure 5.54: Block-of-flats embodied CO₂ breakdown (stages A+B4)</i>	176
<i>Figure 5.55: Block-of-flats embodied cost breakdown (stages A+B4)</i>	177

Chapter 6

<i>Figure 6.1: Terrace house optimisation results and pareto front comparison: LCCF/LCC (left), annual energy intensity/annual energy cost (right).</i>	179
<i>Figure 6.2: The LCCF and LCC performance of the optimal annual performance model, against the LCCF/LCC pareto front and optimisation search space</i>	180
<i>Figure 6.3: Terrace house, bungalow and block-of-flats energy intensity (kWh/m²/y) and LCCF (kgCO₂e/m²/60 years) as performance evaluation metrics.</i>	182
<i>Figure 6.4: Terrace house, bungalow and block-of-flats LCCF, excluding (left) and including (right) embodied CO₂ of demolished building components</i>	184
<i>Figure 6.5: Adjusted (left) and un-adjusted (right) LCC aggregated costs of a terrace house refurbishment</i>	191
<i>Figure 6.6 Adjusted (Top) and un-adjusted (bottom) LCC stages breakdown, by life cycle stage of a terrace house refurbishment</i>	192
<i>Figure 6.7: Adjusted (left) and un-adjusted (right) LCC embodied/operational breakdown of a terrace house refurbishment</i>	193
<i>Figure 6.8: Life cycle normalisation: Floor area (left), volume (middle) and absolute value (right)</i>	195
<i>Figure 6.9: Short term (20-years) refurbishment/replacement LCCF comparison</i>	198

List of Tables

Chapter 2

<i>Table 2.1: To refurbish or to Replace? - Current debate</i>	34
<i>Table 2.2: Scope of the systematic literature review</i>	55
<i>Table 2.3: Operational energy calculation methods, used for the calculation of operational CO₂e emissions (of the papers that mentioned the method they have used)</i>	56
<i>Table 2.4: Number of papers that presented data about the different life cycle steps (out of a total of 48 papers and 263 buildings)</i>	56
<i>Table 2.5: Case study buildings floor area (of the papers that mentioned the metric they have used). (a) Included expressions such as: "Heated floor area" or "Habitable space". (b) Included expressions such as: "Net floor area", "Useable area" or "Letable area". (c) Included expressions such as: "Building area", "Floor area", "Overall area" or included no description</i>	57
<i>Table 2.6: Embodied CO₂e calculation method. (a) Databases such as Bath-ICE, Athena, PCT ITEC and others. (b) A combination of databases, EPD and independent calculations. (c) tools such as Gabi, SimaPro and Eco-Invent.</i>	57
<i>Table 2.7: Summary of the most common optimisation algorithms in the built environment</i>	71 – 72

Chapter 4

<i>Table 4.1: Building properties for optimisation and their possible values</i>	106
<i>Table 4.2: Life cycle stages</i>	106
<i>Table 4.3: Pilot study 1 life cycle scope (based on BS EN 15978:2011)</i>	107
<i>Table 4.4: Pilot study 1 findings summary</i>	110
<i>Table 4.5: Allowed room dimension range</i>	115
<i>Table 4.6: Best and worst geometries surface-to-volume ratio</i>	116
<i>Table 4.7: Pilot study 2 findings summary</i>	118
<i>Table 4.8: Pilot study 3 life cycle scope (based on BS EN 15978:2011)</i>	121
<i>Table 4.9: Building properties for optimisation and their possible values</i>	121
<i>Table 4.10: Pilot study 3 findings summary</i>	124

Chapter 5

<i>Table 5.1: Study life cycle scope (based on BS EN 15978:2011)</i>	130
<i>Table 5.2: Sources of data for the CO₂ emissions involved in the different life cycle stage</i>	130
<i>Table 5.3: Sources of data for the costs involved in the different life cycle stage</i>	131
<i>Table 5.4: Existing buildings build-ups (materials that were kept in the refurbishment scenario are highlighted)</i>	135
<i>Table 5.5: Case study 1 - PLOOTO inputs – possible room sizes and proximity matrix</i>	140

<i>Table 5.6: Case study 2 PLOOTO inputs – possible room sizes and proximity matrix</i>	153
<i>Table 5.7: Case study 3 - PLOOTO inputs – possible room sizes and proximity matrix</i>	166

Chapter 6

<i>Table 6.1: ‘Block-of-flats’ refurbishment and replacement differences summary</i>	195
<i>Table 6.2: Embodied and Operational performance comparison (Embodied emissions = life stage A, operational emissions = life stages B4, B6 and B7)</i>	199

List of abbreviations

AJ	Architect's Journal
ANN	Artificial Neural Network
BIM	Building Information Modelling
DSM	Dynamic Simulation Models
EE	Embodied Energy
EOL	End of Life
EPD	Environmental Product Declarations
FEA	Finite Element Analysis
GA	Genetic Algorithms
HPC	High Performance Computing
ICE	Inventory of Carbon and Energy
IDF	Input Data File
LCA	Life Cycle Analysis
LCC	Life Cycle Cost
LCCF	Life Cycle Carbon Footprint
LCE	Life Cycle Energy
LCI	Life Cycle Inventory
LCIA	Life cycle impact assessment
LCS	Life Cycle Studies
M&S	Modelling and Simulation
MOGA	Multi Objective Genetic Algorithms
NCM	National Calculation Method
NPV	Net Present Value
NSGA-II	Non-Sorting Genetic Algorithms - II
OE	Operational Energy
OERC	Operational Energy-Related CO ₂
PHPP	PassivHaus Planning Protocol
PLOOTO	Parametric Lay-Out Organisation generaTOr
SAP	Standard Assessment Method
SBEM	Simplified Building Simulation Models
SERT	Sustainable Energy Research Team
WLC	Whole Life Cost
WWR	Window to Wall Ratio

1. Introduction

With the constant increase in demand for new dwellings, the refurbishment of existing buildings is considered to have the potential to contribute to the reduction of the environmental impact of buildings. Building refurbishment is considered to be the most cost-effective way of achieving environmental impact reductions, however, a comprehensive assessment of the benefits of refurbishment versus replacement has yet to be undertaken. This chapter introduces the background for the 'refurbishment versus replacement' debate. It states the research question, summarizes the research approach, present the tools that were used for the execution of this research, and lists the main contributions of this study.

1.1. Context

According to the Department of Energy and Climate Change (2011), the built environment is responsible for 40% of the global energy consumption. The global construction industry is also responsible for approximately 40% of overall consumption of raw aggregates and 25% of the world's wood consumption (Horvath, 2004; Langston and Langston, 2008; European Commission, 2013). The UK is one of the world's highest CO₂-emitting countries (Olivier *et al.*, 2013). Following the Kyoto protocol of 1992 and the Paris 2015 UN Climate Change Conference, the UK government has committed to reducing at least 80% of its CO₂ emissions, compared to its 1990 baseline figures, by 2050 (Department of Energy and Climate Change, 2011). The buildings industry, therefore, can have a significant contribution to the success of this commitment.

While much of the effort for improving building energy efficiency is focused on new buildings, the environmental performance of existing buildings can have an important role in reducing the environmental impact of the built environment. In the UK, new buildings account for around 1% of the total building stock every year (Power, 2008), and around 75% of the housing stock that will still remain in 2050 has already been built (Sustainable Development Commission, 2007). To achieve the UK government's CO₂ reduction targets in an economically viable way, a detailed investigation is required,

aiming to identify the most efficient reduction mechanism: the refurbishment of existing buildings or their demolition and re-building of new ones.

The debate regarding the refurbishment or replacement of existing buildings is highly complex as it involves an examination of a wide range of aspects, both qualitative (social, cultural and aesthetical) and quantitative (environmental or economic) (Power 2008, Bullen & Love 2010, Roberts 2008). Furthermore, while the environmental impact of buildings is the result of processes that occur throughout their life-cycle such as construction, usage and demolition, current building performance improvement efforts focus mainly on the performance of buildings only once they are built and occupied.

Therefore, there is a need for a more holistic and comprehensive approach for clearly defining and evaluating building performance, in the context of their life cycle, to better inform decision makers and stake holders when they are faced with the two design alternatives: refurbishment or replacement.

1.2. Research Scope

1.2.1. Research Aims and Objectives

In considering that difficulties in identifying a favourable design solution when considering refurbishments and replacements, this research aims to present a general framework for evaluating the environmental and economic benefits of refurbishment and replacement projects. In particular, this study aims to evaluate the Life Cycle Carbon Footprint (LCCF) and Life Cycle Cost (LCC) of the refurbishment of existing buildings and of their replacement (demolition and extraction of new buildings), to identify the preferable design alternative, in an aim to address the following research question:

Is the optimal refurbishment of existing buildings preferable over their optimal replacement, in respect of Life Cycle Carbon Footprint (LCCF) and Life Cycle Cost (LCC)?

Further to the main research question this research also aims to:

- Identify key stages in the life cycle of buildings and evaluate their relative contribution to the life cycle performance of buildings.
- Explore how CO₂ and cost can be used as decision making metrics, for the evaluation of building performance.
- Identify the potential use of life cycle performance evaluation methods, integrated with generative design programming and optimisation tools, as early design decision-making strategies when considering the refurbishment or replacement of existing buildings.

By identifying the key issues related to the context of this research, and following the abovementioned research questions and aims, the following research objectives have been set:

- To develop a computational framework, by which a non-biased comparison between the performance of optimal refurbished designs and that of optimal new buildings can be carried out, to minimise their LCCF at a minimal overall cost.
- To explore how LCCF and LCC analysis can impact building design decisions and examine the ways they can be integrated with other design criteria, protocols and methods during the current process of building design.
- To conduct a rigorous analysis to identify the building components and life cycle stages which contribute most to the performance of refurbishment and replacement buildings, when examining their LCCF and LCC.
- To discuss and highlight the limitations involved with frameworks for evaluating life cycle performance, their calculation methods and the metrics used for evaluating building performance and discuss the way these might affect building performance evaluation and conclusions of performance evaluation studies.

1.2.2. Research Approach Summary

Following a comprehensive analysis of available research methods, a comparative case study analysis was adopted as the main approach for this research. This involved a comparison of the calculated LCCF and LCC of optimal refurbished case study models with that of their replacements. For this reason, this study has utilised two complimentary research strategies: Modelling and Simulation (M&S) and Multiple Case Study Analysis.

- A. Modelling and Simulation (M&S) is an approach for the representation of an observed system, and for examining the relationships between different components within it, to explain how these affect the system behaviour (Wainwright & Mark, 2005). Due to recent developments in computer science and software application, computational M&S has become an important method for theory development (Tolk, 2010).

In the discipline of the built environment, for the aim of predicting their thermal behaviour, buildings are often abstracted and represented either by mathematical expressions, or digitally, through the use of computational applications that allow a more detailed representation of the buildings properties.

- B. Case study analysis is a technique that is used for the investigation of the dynamics of phenomenon, through the use of a set of comparative measures and techniques. The investigation of multiple case studies simultaneously is often used for the identification of patterns and similarities across different examined cases, as well as for the development of theories or as method for validation of research results (Eisenhardt, 1989; Darke, Shanks and Broadbent, 1998; Amaratunga and Baldry, 2001; Amaratunga *et al.*, 2002; Yin, 2014).

The proposed computational framework and methodology were developed, tested and validated through the use of three pilot case-studies, to ensure the robustness of each computational framework component. The complete framework was then applied on the actual research case studies.

1.2.3. Research Tools and Techniques

The proposed research necessitated the integration of several research and analysis techniques. To perform a comparative analysis between multiple design alternatives and select an optimal design solution efficiently, several frameworks and analysis tools had to be used simultaneously, using a single framework. These included:

Life Cycle Performance: The performance of buildings in this research was evaluated in respect of their life cycle. This included the integration of the EN 15978:2011 and ISO 15686-5 protocols for the calculation of LCCF and LCC values.

Thermal Simulations: To calculate LCCF and LCC values, operational energy use should be calculated (for space and water heating, as well as for lighting). This required the integration of a thermal simulation tool within the framework.

Generative design: To compare the performance of refurbished buildings with that of new ones, a large number of building design alternatives, in the form of a thermal simulation model, had to be generated, modelled, simulated and evaluated. To enable this, a designated application for the automated generation of building spatial arrangements and layout designs has been developed.

Mathematical optimisation frameworks: These are mechanisms for the rapid search after solutions for a given problem in an efficient way. Mathematical optimisation mechanisms are often implemented through the use of computational applications, which can compile an automated searching procedure while keeping computational resources relatively low. For the implementation of the optimisation mechanism, a Genetic Algorithm (GA) application has been developed, based on Non-Sorting Genetic Algorithms – II (NSGA-II).

This research made use of UCL's High Performance Computing (HPC) services – an infrastructure network of a cloud computing system – to carry out resource-intensive

computational procedures. Legion enables running parallel computational processes using multiple computer cores which can result in significant savings of time.

1.3. Contribution

This research presents an assessment of the potential environmental and cost benefits of refurbishments and replacements of existing buildings. In completing the main objectives of this study, its original contributions are stated below:

1.3.1. Contribution to Knowledge and List of Papers

A. Establishing a Computational Framework Linking Computational Programming with Research of the Built Environment:

This research has developed an early-design performance assessment framework, for optimising building designs. The framework, which introduces an integration between generative design programming, mathematical optimisation, thermal simulations and life cycle performance protocols, has been described and tested throughout this work. The computational framework can assist scholars in further examination of building properties and performance trade-offs, and further extend the current body of knowledge in this research domain.

B. Life Cycle Performance

The research sets out an extended discussion that examines the limitations of commonly-used performance proxies, in particular when comparing the performance of refurbished buildings and their replacements. Furthermore, the analysis discusses limitations of life cycle performance protocols and explores various aspects of life cycle performance analysis, and the impact they might have on the outcomes of building performance evaluations and building designs. These included: the use of LCCF and LCC as performance metrics, building performance at various life-stages, the impact life expectancy on life cycle performance and more.

C. LCCF Benchmarks and Case Study Analysis Findings

This research sets out, for the first time, a benchmarking framework, based on a systematic review of the LCCF of case study buildings of various types and uses from around the world. Through the synthesis of the overall outcome of the reviewed studies, the framework presents a comparison between the LCCF of refurbished buildings and their replacements, to identify the optimal design alternative.

Furthermore, the research sets out an evidence-based discussion, presenting a new and original body of knowledge regarding the life cycle performance of refurbished and replaced buildings. These include the evaluation of the LCCF and LCC of selected case study buildings, in regard to their refurbishment and replacements, and a detailed analysis of various aspects of life cycle performance (e.g.: a year-by-year performance analysis, embodied versus operational performance, the contribution of different building components to the environmental performance of buildings etc.).

List of Published Journal Papers:

- **Schwartz, Y.,** Raslan, R., Mumovic, D. (2018), 'The life cycle carbon footprint of refurbished and new buildings – A systematic review of case studies', *Renewable and Sustainable Energy Reviews*, 81. doi: 10.1016/j.rser.2017.07.061.
- **Schwartz, Y.,** Raslan, R., Mumovic, D. (2016), 'Implementing multi objective genetic algorithm for life cycle carbon footprint and life cycle cost minimisation: A building refurbishment case study'.*Energy*,97,https://doi.org/10.1016/j.energy.2015.11.056.
- **Schwartz, Y.,** Raslan, R., Mumovic, D. (Submitted for publication), 'An Integrated Thermal Simulation, Optimisation & Building Generative Design Framework: A Life Cycle Performance Approach' – Submitted to *Automation in Construction*.
- **Schwartz, Y.,** Raslan, R., Mumovic, D., 'Refurbish or Replace? The Life Cycle Carbon Footprint (LCCF) and Life Cycle Cost (LCC) of Refurbished Buildings and Their Replacements' – In preparation for submission to *Energy and Buildings*.

List of Published Conference Papers:

- **Schwartz, Y.**, Raslan, R., Mumovic, D. (2018), 'Refurbish or Replace: Optimising Refurbished and New Building Designs for Life Cycle Carbon Footprint and Life Cycle Cost Minimisation' . *Proceedings of the Building Simulation and Optimisation (BSO)*, Cambridge, UK.
- Eleftheriadis, S., **Schwartz, Y.**, Raslan, R., Duffour, P., Mumovic, D. (2018), 'Integrated Building Life Cycle Carbon and Cost Analysis Embedding Multiple Optimisation Levels'. *Proceedings of the Building Simulation and Optimisation (BSO)*, Cambridge, UK.
- **Schwartz, Y.**, Raslan, R., Mumovic, D. (2017), 'Integrated Building Performance Optimisation: Coupling Parametric Thermal Simulation Optimisation and Generative Spatial Design Programming'. *Proceedings of the 15th International Building Performance Simulation Association (IBPSA)*, San Francisco, CA, USA, <https://doi.org/10.26868/25222708.2017.316>
- **Schwartz, Y.**, Raslan, R., Mumovic, D. (2016), 'Semantically Enriched BIM Life Cycle Assessment to Enhance Buildings' Environmental Performance'. *Proceedings of the CIBSE Technical Symposium*. Edinburgh, UK
- **Schwartz, Y.**, Raslan, R., Mumovic, D. (2015), 'Multi-objective genetic algorithms for the minimisation of the life cycle carbon footprint and life cycle cost of the refurbishment of a residential complex's envelope: a case study'. *Proceedings of the Symposium on Simulation for Architecture & Urban Design*. Alexandria, Virginia, USA. ISBN: 978-1-5108-0104-2

1.3.2. Impact Statement - Contribution to Industry

This research, as informed by the needs of the industrial sponsor, was initiated to introduce the life-cycle-performance approach as a proxy for evaluating the performance of refurbished buildings and their potential replacement, where a significantly narrower

perspective towards 'performance' is currently used in both in academia and in practice in the UK. This research has made impact on various domains:

- During this research, an early design decision-making computer application was developed and tested, for the evaluation the benefits of refurbishment or replacement of existing buildings. This application, which streamlines the generation of optimal refurbished and new buildings into a single process, can assist decision makers – stakeholders, designers, public officials or authorities – by informing them of the favourable approach towards the regeneration of existing buildings or estates.
- In completing this research, a Building Information Modelling (BIM) tool for the integrated automated calculation of the embodied CO₂ of buildings was developed. The tool – a Revit plug-in – is designed to seamlessly calculate the embodied CO₂ of used building components and export them in a .csv format for further analysis and is being used at the industrial sponsor's practice. The plug-in can inform practitioners and design teams and assist them in evaluating the embodied CO₂ performance of their designs at the different stage of design.
- As part of this study, a computer application for the automatic generation of building layout and spatial arrangements was developed. Though not directly related to buildings performance analysis, this application can support building design teams in the tasks of layout design and spatial arrangements in an efficient and rapid way.

The author of this thesis assisted the sponsor in various activities, including:

- Carrying an Embodied CO₂ analysis for various optional façade designs.
- Conducting "Project Surgeries" – reviewing the sustainability aspects of projects within the office, running thermal and lighting simulation and reviewing projects.
- Delivering talks and CPDs to office staff, introducing concepts such as thermal performance, thermal simulations, embodied CO₂ in buildings, buildings life cycle and

other sustainability-related issues. This also included assisting in organizing and running “Hawkins Brown green week” – an internal event aimed to engage individuals within the office with the “Hawkins Brown Sustainability Group”.

1.4. VEIV (Virtual Environments, Imaging and Visualisation) - Industrial Sponsor: Hawkins Brown LLP

This research was carried out as a part of the VEIV (Virtual Environments, Imaging and Visualisation) program. VEIV aims to direct research in industry to maintain strong industry links. The program is run by the Department of Computer Science and has strong collaboration relationship with the Bartlett Faculty of the Built Environment.

This EngD engaged a collaboration with an industrial sponsor – Hawkins\Brown LLP – an internationally-renowned award-winning practice of over 200 architects, interior designers and urban designers. Founded in 1988 by Roger Hawkins and Russell Brown, the practice has studios in London and Manchester, holding a portfolio of works designing buildings across multiple sectors, including infrastructure, education, housing and commercial spaces, from urban scale to interior design.

In recent years Hawkins\Brown has won or been shortlisted for numerous awards. Among those was being shortlisted in the RIBA Stirling Prize (2013) for the Sheffield’s Park Hill refurbishment scheme - Europe’s largest listed building, or AJ100 (Architects Journal) Sustainable Practice of the year (2013).

Sustainability, refurbishments and re-developments are one of the practice’s core values, aiming to promote low-carbon buildings and improve buildings performance throughout their lives. These include projects such as:

- Here East – transforming the broadcast centre at the Olympic Park into a mixed-use commercial educational and urban space.

- Adar Grove – The design of 500 affordable existing and new homes at a PassivHaus standard. Once completed, this will be the biggest PassivHaus development in Europe.
- 22 Gordon Street – The refurbishment of the old home of the Bartlett School of Architecture. The design doubled the available school space while retaining and extending the building's original structure

1.5. Thesis Structure

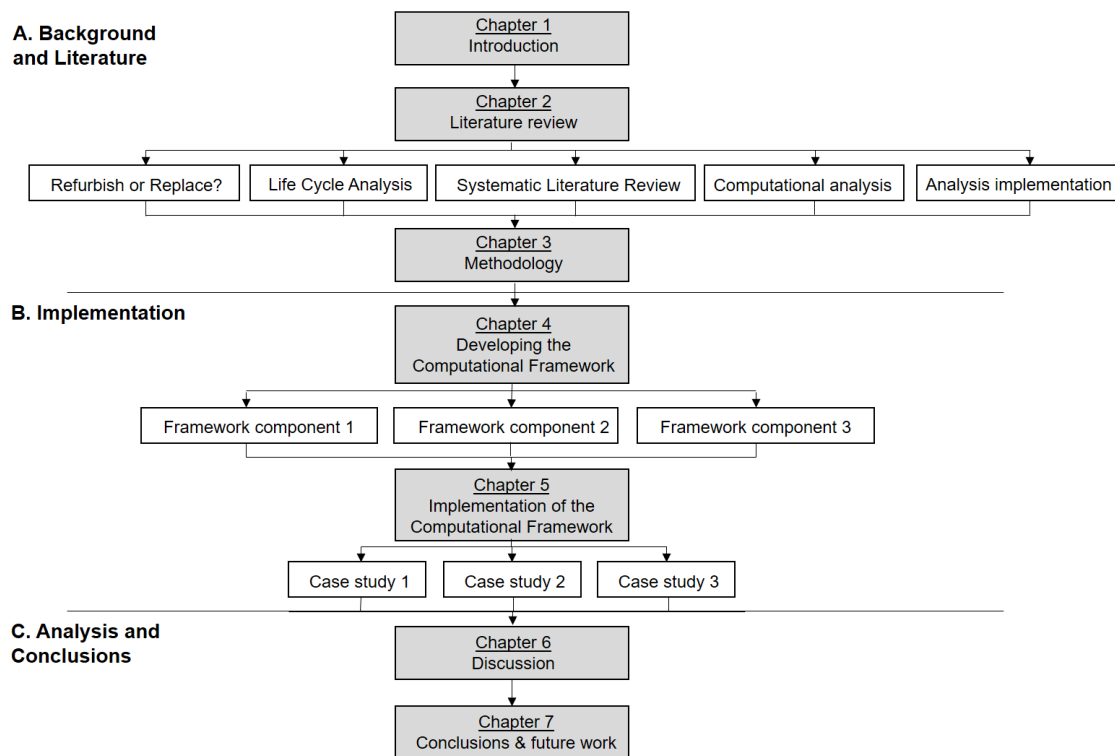


Figure 1.1: The thesis structure and list of chapters

The chapters of this research are divided into three main thematic parts: Background and Literature, Execution and Analysis and Conclusions. Each chapter includes a short introduction and a “chapter summary” discussion section at its end. The chapters are set as follows:

A. Background and Literature

- Chapter 1: Introduction

This chapter introduces the background and context of the research, focusing on the research aims and objectives. The research scope and contribution to knowledge are also presented, as well as introduction of the research industrial sponsor.

- Chapter 2: Literature Review

A review of the relevant literature. This includes an introduction of building life cycle carbon footprint and life cycle cost analysis, and a detailed investigation of the current state of life cycle research. The review also covers the background and literature related to the methods used in the study, in particular an analysis of the state-of-the-art generative design methods and a review of mathematical optimisation techniques.

- Chapter 3: Methodology

This chapter introduces the research approach and the research design. It describes the principles that stand behind the main approaches used in this research: comparative case studies and modelling and simulations, and introduces the tools and frameworks that were used, as well as those that were developed, for the execution of this research.

B. Implementation and Results

The research was carried by undertaking six core optimisation runs. The first three were used during the development, testing and validation of the proposed computational framework and study design, through the examination of a series of pilot studies. The last three were the evaluation of the main case studies – the comparison between the LCCF and LCC of refurbished buildings and their replacement.

- Chapter 4: The Development, Testing and Validation of the Proposed Computational Framework

To develop, test and validate the outputs of the proposed computational framework and study design, three simplified small-scale pilot studies were carried out, examining and validating different aspects of the proposed research methods and

tools. Each study is described through its aims and context, followed by a description of its execution and ends with a set of results, a discussion and conclusions.

- Chapter 5: Implementation and Main Study Results

Once the methodology had been tested and evaluated, it was applied on the main case studies. This chapter start by presenting the case studies scope and the studies assumptions. For each case study, a description of the case study building is the presented, and the refurbishments and replacements optimisation results and analysis are set out.

C. Analysis and Conclusions

- Chapter 6: Discussion

An analysis of the study outputs is presented in this chapter, examining the results and assessing discusses different aspects of the research analysis. This ranges from examining building performance metrics, through a critical discussion of LCA protocols, future potential developments in the life cycle performance evaluation of building and a discussion regarding the study limitations.

- Chapter 7: Conclusions and Future Work

This chapter highlights the key conclusions of this research, in considering the research aims and objectives. Original contribution to knowledge is discussed, and opportunities for future research are identified, especially those related to the research limitations and to the contribution to current knowledge.

2. Literature Review

This chapter covers the relevant background issues, in the context of this research. The current state of the debate regarding the 'refurbishment or replacement of existing buildings' is firstly presented. This is followed by an introduction to the Life Cycle Analysis (LCA) concept and, as well as to the relevant frameworks and protocols - focusing on Life Cycle Carbon Footprint (LCCF) and Life Cycle Costs (LCC). The advantages of refurbishments and replacements are then examined, through a systematic literature review of the LCCF and LCC of new and refurbished buildings. Lastly, a review of current state-of-the-art computational analysis techniques is presented, focusing on computational optimisation methods in the building industry, and on generative design programming. Both concepts were used in the execution of this research.

2.1. To Refurbish or to Replace – Review of Evidence

Although both the refurbishment of existing buildings and the construction of new ones have the potential to significantly improve the life cycle impact of buildings (Power, 2008; Ding, 2013; Goldstein et al., 2013), the different alternatives offer performance improvements at different stages of the building's life: while refurbished buildings allow the re-use of some parts of the existing structures and save part of their embodied resources, new buildings have a higher potential for operational use improvements due to better potential orientation, higher flexibility in their spatial arrangement and the integration of advanced building technologies.

Although there is a growing number of studies that recommend refurbishments to replacements (as refurbishments are often perceived as more environmentally and economically responsible), evidence for this claim is still non-established and the actual benefits of either option is still not clear (Bell et al., 2014, Bullen & Love, 2010, Goldstein et al., 2013, Power, 2008).

The nature of the problem, however, makes it hard to gather evidence and reach an agreed upon conclusion: Most studies evaluate the benefits of each alternative differently.

Aspects such as energy, CO₂ and cost are often examined, but also are social, aesthetical and cultural ones. Bullen & Love (2010) show that while the choice between refurbishment and replacement is often driven by economic reasons, environmental aspects have a growing impact on this decision.

And yet, while the refurbishment of existing buildings has gained an increasing interest in recent years, studies still focus on relatively narrow aspects of the problem: In a recent review, Vilches et al. (2017) examined the life cycle performance of refurbished buildings, however, the review focused on the technical aspects of using the Life Cycle Analysis (LCA) framework, rather than on the actual performance of refurbished or new buildings. Li et al. (2017) and Abdallah et al. (2015) examined the potential of incorporating low-CO₂ refurbishments measures in existing buildings, without comparing the performance of the refurbishment with that of a replacement design.

Only a handful of studies have tried to examine the potential benefits of refurbishment or replacements by reviewing case studies. It is important to note that even when doing so, most studies often compared the performance of a refurbished building with a very limited number of replacement alternatives (a single replacement, in most cases). Optimisation processes are usually not carried out, and as a result, there is no way to verify that the best design alternatives have been compared. Though these case studies present a limited scope of building performance optimisation, they are of value as they are the only examples to ever compare refurbishments and replacements.

The examined studies can be categorized into three different groups, reflecting their overall conclusion (Table 2.1):

Study	Replacement	Refurbishment	Ambiguous
ARUP, Capital & Government (2010)			X
Alba-Rodríguez (2017)		X	
Boardman et al. (2005)			X
Ding (2013)		X	
Empty Homes Agency (2008)			X
Erlandsson & Levin (2004)		X	
Gaspar & Santos (2015)		X	
Hawkins & Mumovic (2014)	X		
Itard & Klunder (2007)		X	
Rønning et al. (2009)	X		

Table 2.1: To refurbish or to Replace? - Current debate

2.1.1. Evidence in Support of Replacement

Some studies have claimed that replacement of existing buildings is the preferable alternative. Rønning et al. (2009) have compared the refurbishment or replacement of an existing office building in Norway and concluded that in terms of LCCF over an assumed 60 years life span – replacement is preferable. The study also showed that the CO₂ payback time in this case was 15 years.

Hawkins & Mumovic (2014) have analysed the 60 years LCCF of two university building case studies. Comparing the performance of four refurbishment scenarios and one replacement alternative – the study has shown that the new-built scenarios achieved the biggest impact reductions.

2.1.2. Evidence in Support of Refurbishment

Other studies, however, concluded that refurbishment is the better option. Itard & Klunder (2007) have examined different life cycle aspects of two post-war residential blocks in the Netherlands. The study applied four different scenarios on each building: simple maintenance, envelope refurbishment, extensive intervention and replacement. Though the study does not explain how calculations have been made, both case studies showed that replacement was the worst option, while envelope refurbishment and extensive intervention were the best.

Erlandsson & Levin (2004) have evaluated the national-scale impact of refurbishments and new buildings in Sweden and presented a detailed analysis of a single case study complex over 30 years. The study concluded that refurbishments had reached better life cycle energy performance. It is hard to understand from the study, however, how the new-building was designed, and which energy-performance measures were implemented in it.

Alba-rodríguez et al. (2017) have examined the refurbishment of an existing residential block in Seville, Spain, and compared it with its replacement. The building had suffered damages during its construction and was therefore assessed for its refurbishment or replacement. The analysis showed that even in the case of a severely damaged building, the refurbishment alternative resulted with a better environmental and economic impacts.

Gaspar & Santos (2015) have compared the extensive refurbishment and the replacement of a single-family house in Portugal. Both the refurbishment and the new building in the study were exactly the same (i.e., though it was possible to improve the design in the new-built option, this has not been done). As the only difference between the two alternatives was their embodied energy (which was far greater in the replacement alternative), the expected conclusion was that the new building had higher overall energy consumption.

Ding (2013) has compared three types of residential buildings in China: refurbished, reconstructed (new-built, but with the same style as the refurbished ones) and a new flat in a high-rise building. The study favored refurbishments rather than the new buildings, although the actual results were somewhat ambiguous. Also, the study based its conclusion on the buildings' embodied energy and CO₂ only – an operational energy or CO₂ analysis was not presented.

2.1.3. Ambiguous Results

Some studies also presented ambiguous conclusions or stated that a clear answer could be drawn. For example, a report by the Empty Homes Agency (2008) has examined the

LCCF of six different residential buildings over an assumed life span of 50 years - three of the case studies were newly built and the other three – refurbished. The study has shown that the difference between the LCCF of an average new building and that of a refurbished one were negligible. As both the best and the worst performance buildings were refurbished, the study concluded that refurbished buildings can be as environmentally efficient as new ones, but also that there is no clear answer which approach is better.

A study by ARUP for Capital & Government (2010) has examined various scenarios in the life time of an existing office building. Three scenarios varied from routine maintenance and periodic small refurbishments to demolition and the construction of a new state-of-the-art sustainable building. Analysis has showed that demolishing a well-performing building makes no sense in terms of life cycle environmental impacts, whereas in the case of poor performing buildings, replacement by an efficient new design might be the better solution.

Boardman et al. (2005) have presented a "bottom-up" model of the UK building stock to examine the country's ability to reach its CO₂ reductions targets. The study concluded that while most existing buildings can be refurbished, the worst buildings (14% of the total stock) should be replaced.

2.1.4. 'Refurbish or Demolish' in The UK Context

In the UK, 28 million buildings exist: of which, almost 22 million are homes and the rest are non-residential, responsible to around 26% and 18% of the UK's total CO₂ emissions respectively (Delay, Farmer and Jennings, 2009; BRE, 2012). Boardman et al. (2005) note that by the year 2050 there will be almost 32 million households in the UK, and a study by the Chartered Institute of Building (2013) points out that most of those already exist today. A study by the BRE shows that more than half of the UK dwellings are more than 50 years old, and that around a fifth is more than 100 years old.

The debate regarding refurbishment or replacement of existing buildings has gained an increasing interest in the UK in recent years, especially since the government's CO₂ reduction targets were introduced. Most UK studies, however, emphasis the cultural and social aspects of refurbishments versus re-building in addition to the environmental and economic factors.

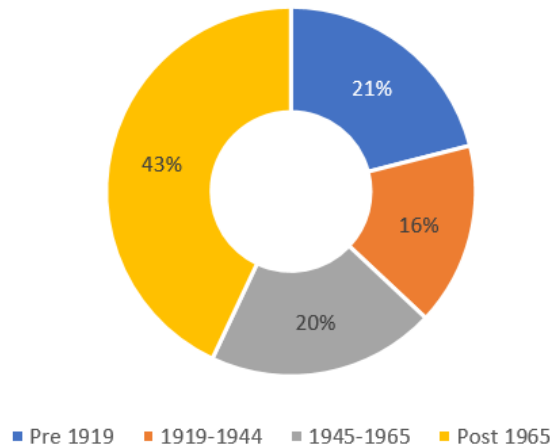


Figure 2.1: The UK Housing Stock. BRE unpublished research, cited by The National Refurbishment Centre (2012)

One of the earliest and most influential papers debating refurbishments and replacements was written by Power (2008), who reviewed studies by both independent and public bodies in the UK discussing this question (such as the Royal Commission on Environmental Pollution, English Heritage, The Empty Homes Agency and others). Power summarized their arguments and evidences for and against each alternative and concluded that refurbishment is the more sustainable approach and should therefore take place whenever possible. Despite Power's thorough investigation, the majority of arguments supporting this view were not based on quantified evidence, and only a very limited number of actual case studies were discussed. Despite its thorough investigation, however, the majority of arguments supporting this view were not based on any quantified evidence, and only a very limited number of actual case studies were discussed. In addition, though the review heavily criticised what was presented as the 'evidence for demolition' but was more accepting of the 'evidence for refurbishment' alternative.

A more recent study with similar conclusions had focused on the refurbishment or replacement of social houses in the UK (Bell et al., 2014). Like Power, a limited number of actual case studies have been examined. The paper suggested that refurbishments can achieve similar levels of energy consumption as new buildings while avoiding the CO₂ emissions of demolition and construction, and therefore concluded that refurbishments are preferable. The Energy Saving Trusts (cited by Crawford et al., 2014), examining three types of refurbishments (low, middle and high costs), suggested that a 60% CO₂ emissions reduction by 2050 is only possible through a "deep retrofit", which requires an overall treatment to the building fabric.

While the studies examined presented a comprehensive and thorough analysis, the balance between the potential life cycle CO₂ savings of the different approaches has, to date, not been thoroughly investigated and evidence is still unestablished (Power, 2008; Bell et al., 2014).

Though refurbishments are often claimed to be the more environmentally-responsible alternative, the UK refurbishment market has some practical limitations. The National Refurbishment Centre (2012) notes that 13,000 homes will have to be refurbished every week to reach the UK government's CO₂ reduction targets. A much more relaxed estimation by Chaytor et al. (2014) suggests around 60,000 homes will have to be refurbished every year in the next 35 years to meet demands. Chaytor et al. also states that building refurbishment is a viable option as long as the structure of the building does not require an extensive treatment, and as long as the complexity of the refurbishment works is reasonable. Bullen & Love (2010) add that UK building owners often avoid property refurbishments due to issues related to commercial risks, health and safety and maintenance.

2.2. Life Cycle as Performance Metric in the Built Environment

2.2.1. Background

Sustainable design metrics and tools are often used for the quantification of sustainability and profitability of a development; however, they are often quite limited in their scope. To evaluate the overall impact buildings have on their environment, a more comprehensive Life Cycle approach should be taken.

Life cycle assessments are carried in what is referred to as a 'cradle to grave' approach (Duda and Shaw, 1997; ISO 14040, 2006; ISO 14044, 2006). They use assessment and management frameworks that aim to simplify the decision-making processes of manufacturing and consumption, with regard to various aspects, such as energy consumption (Life Cycle Energy- LCE), CO₂ emissions (Life Cycle Carbon Footprint - LCCF), costs (Life Cycle Cost - LCC) or environmental impacts (Life Cycle Assessment - LCA). Chau et al. (2015) point out that though different assessment methodologies have similar objectives, and though they are usually based on similar protocols - their findings do have some discrepancies as they often use different metrics for evaluation.

2.2.2. Resource Flows in Buildings

The analysis of the life cycle performance of buildings has been a growing research field in recent years (Dixit et al., 2010). Resource flows (energy, CO₂ emission or costs) in the building sector occur at different stages during a building's lifespan; during material extraction, building components manufacturing and building construction, while the building is in use and when it is refurbished and demolished (Hammond & Jones, 2011).

In evaluating the life cycle environmental and economic impacts of buildings, energy flows are used most often, as they are considered "exchangeable" metrics: the unit of energy can be quite easily transformed to other impact categories, such as environmental impacts or overall costs.

Based on Fay et al., (2000), Sartori and Hestnes (2007) and Dixit et al., (2012) the life cycle of buildings resources is composed of the following stages:

Embodied Component: Embodied Energy (EE) - EE describes the sum of the energy required for the manufacturing of a product or a service. In buildings, this includes the energy used for the extraction of raw materials, transportation to and from factories and energy required for construction, maintenance, periodic refurbishments and the replacement of various building components once they are worn out (Fay, Treloar and Iyer-Raniga, 2000). Meta-analysis studies show that EE accounts for between 2-38% of the life cycle energy use in conventional buildings, and 9-46% in low-energy buildings (as the later consume less energy during their operational phase, and their construction is usually more carbon-intensive) (Duda and Shaw, 1997; Feist. W, 1997; Winther and Hestnes, 1999; Scheuer, Keoleian and Reppe, 2003; Fesanghary, Asadi and Geem, 2012).

Operational Component: Operational Energy (OE) - OE shows the energy used for maintaining the thermal and environmental conditions within the building, with a focus on heating, cooling, domestic hot water and lighting (Fay, Treloar and Iyer-Raniga, 2000). Studies by Gustavsson et al. (2010) and Eriksson et al. (2007) show how heating system and the fuel type used for OE generation impact LCA results, as some supply systems and energy generation technologies are more environmentally-friendly than others.

Demolition: End of Life (EOL) - EOL is the energy required for actions related to the demolition of the building and transporting waste to dump sites. EOL in buildings is often accounted under the EE phase, and usually accounts for around 1-3% of the building's embodied and operational energy use (Dixit et.al, 2012).

In the larger context of the life cycle of buildings, two more steps can be considered in an analysis as illustrated in Figure 2.2 – recycling and the incorporation of renewable energy. However, as these components require various assumptions and result in greater uncertainties – they are very rarely accounted for (Sartori and Hestnes, 2007; Bin and

Parker, 2012; Kua and Wong, 2012; Asdrubali, Baldassarri and Fthenakis, 2013; Dodoo and Gustavsson, 2013).

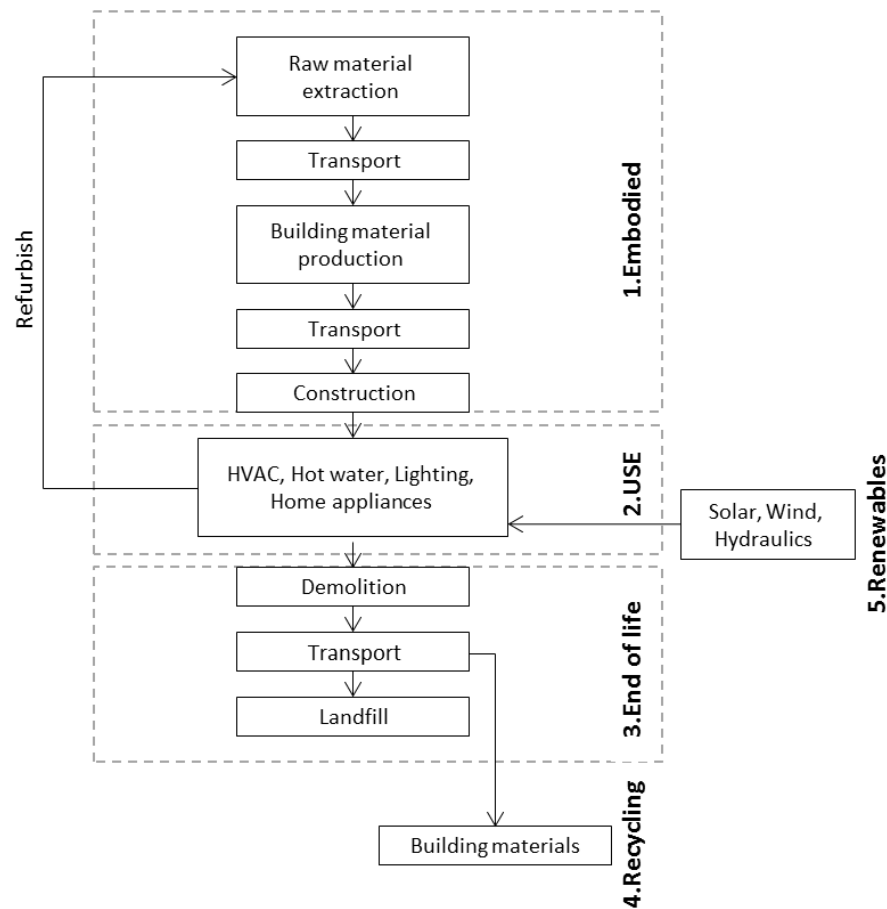


Figure 2.2: Input and output Energy flows in buildings

2.2.3. The Life Cycle Assessment (LCA) Framework

Life Cycle Studies (LCS) methodologies are largely based on the Life Cycle Assessment (LCA) framework - an environmental assessment and management framework that aims to minimise the environmental impact of production processes (ISO 14040, 2006). Life cycle studies are comparative methods – they assist in choosing the best option out of a set of alternatives by comparing the performance of different 'System Units' (a product or a service, or a building in the built environment). Based on ISO 14040: 2006, LCS studies usually include the following components (Figure 2.3):

Goal and Scope – Where the goals of the study and the reasons for carrying it are clearly stated, as well as with whom its results should be communicated. This stage should include a clear description of the study's fundamental components: the system scope and reported metrics, assumptions and limitations, types and sources of data etc.

Life Cycle Inventory Analysis (LCI) – In this step, an inventory of input and output flows of all production processes is formed. All sources within all system and sub-systems of the production process should be identified and quantified individually. This forms an inventory of data that consist the relevant impact (environmental / cost or other) of each element that might be included in the analysis.

Life Cycle Impact Assessment (LCIA) – where the entire system is analysed, based on the different components in the inventory and their relevant impact (environmental / cost or other) is evaluated.

Interpretation – the results of the LCIA are analysed and evaluated, and a set of conclusions and recommendations are laid out. These are summarized to enable the decision-making process in accordance with the aims of the study, as those were described in the first step.

As the steps of LCA studies are quite loose-ended, and as studies might focus on different aspects of the life cycle it might make it impossible to compare the performance of different alternatives. Transparency, therefore, is a key issue in conducting LCA studies. It is essential to share accurate description of the analysis process, to enable others to evaluate and assess the analysis, and fully understand its scope.

Both Life Cycle Carbon Footprint (LCCF) and Life Cycle Cost (LCC) are based on the LCA method. The next two sections describe the details of the LCCF and LCC protocols.

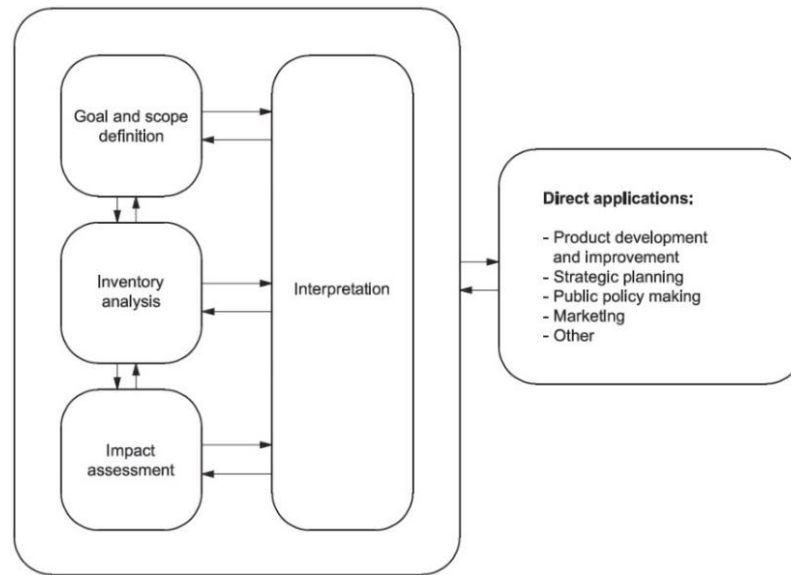


Figure 2.3: The LCA Framework (ISO 14040: 2006)

2.2.4. Life Cycle Carbon Footprint (LCCF) and EN 15978:2011

EN 15978:2011 - Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method - is an adaptation of the LCA - ISO 14040 standard into the discipline of the built environment. The protocol defines five main stages in the life cycle of buildings: product, construction, usage, end-of-life and recycling. These stages are shown on Figure 2.4 and further explained below, using CO₂ emissions as the metric with which life cycle performance is measured.

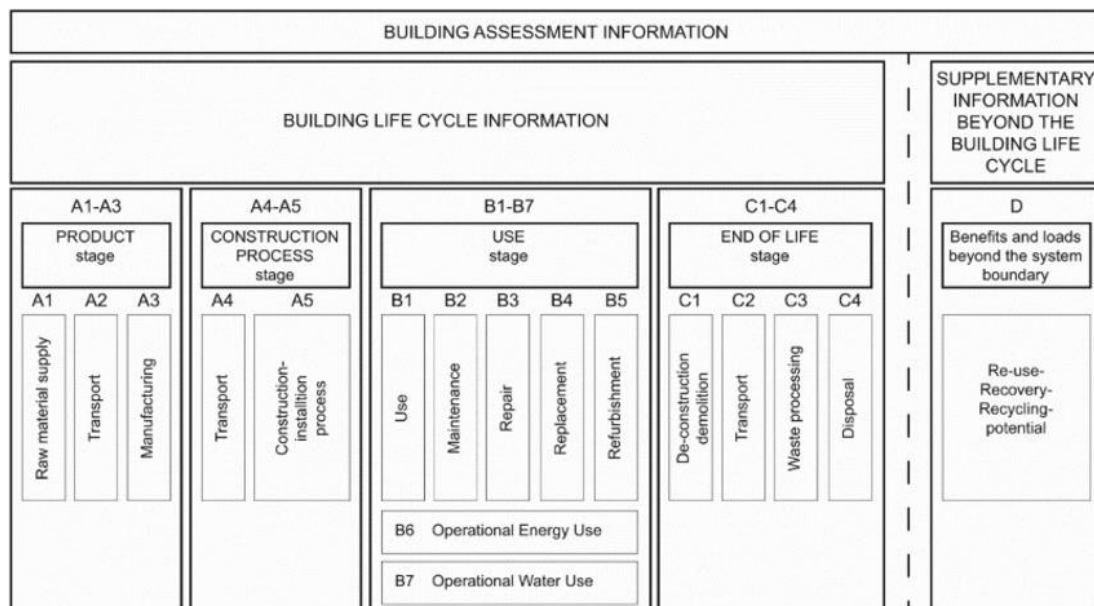


Figure 2.4: Building life cycle, according to EN 15978:2011 (BS ISO, 2011)

A1-A5: Product and Construction Processes – This stage describes the CO₂ emissions during the production of building materials and the construction stage (i.e., the embodied CO₂). Various methods and tools are often used for the calculation of the buildings embodied CO₂. These are classified into the following categories:

A. Material Process-based Calculation

Process-based calculation tools (such as GaBi, SimaPro, Tally and others), enable an assessment of the environmental impact due to the manufacturing processes of individual building material separately. The calculation is made based on a detailed description of the production process of each building material, given by the user (e.g., fuel type used for manufacturing, machinery efficiency, distance to and from the factory etc.).

While this approach might result with a very precise CO₂ emissions figures in simple products, this assessment procedure is not suitable for the life cycle analysis in buildings, as it requires access to manufacturing processes of individual production lines and due to the time it takes to calculate the environmental impact of each building material.

B. Pre-calculated Databases

Another method for calculating buildings embodied CO₂ is using Pre-calculated impact databases. These databases collect the environmental impact values of widely-used building materials and components.

Various pre-calculated databases are available for use however they might have some important differences: Pre-calculated databases are often country-dependent. This is because the type of fuel used for production of energy for manufacturing, and the associated CO₂ emissions, differs between countries. Furthermore, some tools quantify 'environmental impact' differently: Tools such as the Bath Inventory of Carbon and Energy (Bath ICE) (a database which was developed by the Sustainable Energy Research Team (SERT) at the Department of Mechanical Engineering at the

University of Bath) contains lists of building materials and products, their average embodied energy and their embodied CO₂e emissions from cradle to a factory gate (Hammond & Jones, 2011). Other tools, such as CML (developed by the Center of Environmental Science of Leiden University), offer a method for normalizing performance to a range of impact categories, to give greater flexibility in communicating impact assessments (CML, 2015). A series of databases, such as EcoIndicator99 ReCiPe or TRACI, have developed their own 'point-based' weighing system, including impact categories such as human health, ecosystem quality, resource depletion and others (PRE, 2000; European Commission, 2010).

The main advantage of using pre-calculated databases is that they are significantly easier to use compared to the material-process-based approach, and they are easily accessible.

However, while pre-calculated databases are considered to be fairly accurate, it is pointed out that they are likely to be less accurate than the process-based calculation, since by generalising the calculation method to evaluate environmental impacts, impact of specific materials and building components might be missed-out. The pre-calculated database approach, is, therefore, most suitable for use in early design stages, when general figures and trends are identified, and where specific emission values can be used at a later stage.

C. Environmental Performance Certificate (EPD)

The third approach for retrieving product environmental impact is the Environmental Product Declarations (EPD). EPDs are documents that display the environmental impact of specific building materials and products. Commissioned by manufacturers, certified EPDs need to follow a building material environmental assessment protocol – EN 15804:2011 - Sustainability of construction works, to ensure that all EPDs are comparable and produced to a certain level of accuracy.

The main advantage of using EPD is that they deliver an accurate assessment of the environmental impact of specific building material production processes. Since the procedure is standardized and transparent, the assessment outputs evaluated and assessed whenever is needed. On the other hand, the availability of EPDs is still limited as it depends on the manufacturers' good will and their interest to issue one. Furthermore, it is likely that manufacturers with poor production processes, in terms of environmental impacts, will not issue or share their EPD easily, as this might harm their business.

EPDs, therefore, are most suitable for use in an early to detailed design stages, or whenever a specific construction material or product is selected.

B1-B7: Use – In this stage, the CO₂ emissions due to operational use of the buildings are calculated. The use stage can be divided into two main categories:

A. Space Heating, Water Heating and Lighting

This stage shows the emissions related to energy use for the building climate and light controls, and for the consumption of domestic hot water. For the calculation of CO₂ emissions due to operational energy use (space heating, water heating and lighting), energy consumption is firstly calculated, and the relevant energy-to- CO₂ emission conversion factors are then applied to the results.

Energy consumption for space heating and lighting can be calculated using hand calculations, static building energy models or dynamic thermal simulation tools. Energy consumption for domestic hot water is often calculated manually, based on national statistics of typical consumption of domestic hot water.

B. Refurbishment and maintenance

The processes of maintenance, repair, replacement and refurbishments in the 'Use' stage describe measures of recurrent activities for maintaining the building at a functional state.

For calculating these associated environmental impacts, the life expectancy of the different building components needs to be known and their replacement rate should be accounted for. Building components and materials life expectancies are often taken from manufacturers' technical documents or from specialists' guides (builders, quantity surveyors etc.).

C1-C4: End of Life – The End of Life stage includes all demolition-related processes, such as the deconstruction of the building, transport to landfills and other associated demolition actions. Various studies (Chen et al., 2005; Gustavsson et al., 2010; Tae et al., 2011; Dodoo et al., 2014) have demonstrated that demolition-related CO₂ can vary between 0.5 to 6% of the building's embodied CO₂.

D – Loads Beyond the system boundary – This part of the protocol refers to recycling of building materials, and sometimes to the use of renewable energy for the operation stage of the building. As the level of confidence and control of potential recycling – processes that might take place many years in the future – is quite low, these steps are rarely accounted for in LCCF analysis.

2.2.5. Life Cycle Cost (LCC) and BS ISO 15686-5

BS ISO 15686-5: Building and constructed assets - Service life planning. Life-cycle-costing is a LCC framework that aims to assist users by calculating initial capital investment of construction projects, as well as their future operational cost flows. LCC is used for budgeting, cashflow forecasting and option appraisal, at the project end point or at a specific point in time (Bourke *et al.*, 2016; Woodward, 1997; Reidy et al., 2005; Gluch & Baumann, 2004).

BS ISO 15686-5: is a British standard that details the principles of life cycle costing for buildings and construction assets. The standard has been referred to by leading professional organisations such as RICS and BSRIA, and is widely used across the UK

building industry for life cycle costing (Bourke *et al.*, 2016; Churcher and Tse, 2016). LCC is one of the components of the Whole Life Costing (WLC) analysis framework (as shown in Figure 2.5) – an approach that has a broader scope of costing analysis. While LCC focuses on the cashflow related to the building construction and its operation, WLC accounts for potential income flows associated with the construction of the building (e.g., incomes, fees for employees etc.).

BS ISO 15686-5 consists of the following costs components:

Construction costs – these describe the total development costs, including all initial capital costs involved in the realisation of the building, from design to construction. Construction costs are calculated by combining the costs of all building materials and construction works.

Maintenance costs – These include any expense made towards the maintenance and refurbishments, or any action to ensure that the building is fully functional. These might include redecoration, renewal of ran-down building components (e.g.: old windows or roof tiles) or a full refurbishment of the building.

Operation costs – Operation costs refer to all costs incurring in running the building and for the facility management. These mainly include energy consumption for heating and cooling, energy consumption for water heating and electricity consumption for lighting.

As discussed in the LCCF calculations (section 2.2.4), Energy consumption for space heating and lighting can be calculated manually or by using static or dynamic building energy models, and consumption of domestic hot water can be estimated based on national statistical reports. For energy-operational cost calculations, energy costs are taken from local energy suppliers or from national statistic agencies (such as The UK Government Energy Price Statistics, in the UK).

Occupancy costs – In some cases, where building occupiers have explicit usage and operation requirements, these should be addressed in this special category.

End of life costs – End of life costs include any costs associated with the demolition and disposal of the building.

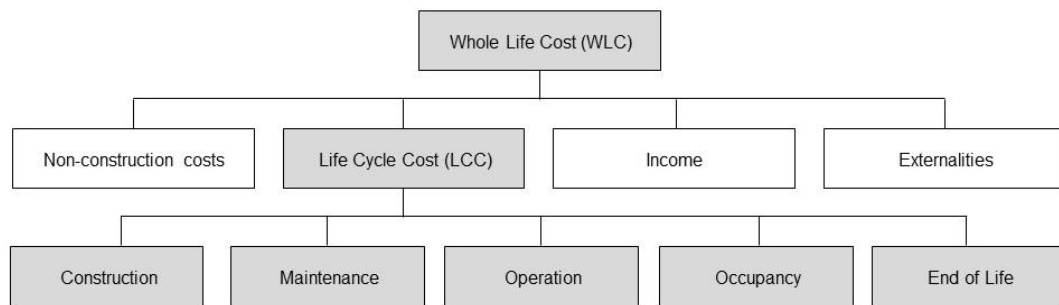


Figure 2.5: Life Cycle Cost (LCC) as part of Whole Life Costing (WLC). Source: adapted from BS ISO 15686-5 (2017).

Discounting - When cost projections are carried out they often consider values at the time of analysis, excluding the impact of inflation on future costs. However, when future costs in different design scenarios are not of similar proportions, or when they are made in different point in time (e.g., when the cost of a future small-scale repair five years in the future is compared with a major refurbishment in twenty years), inflation might have a more significant impact. While environmental impacts are not assumed to degrade over time, the value of money might inflate or deflate as function of time. When the time factor of costs is involved, it should be expressed within the analysis (Gluch and Baumann, 2004). For this reason, BS ISO 15686-5 recommends bringing future costs to a present-day value by using discounting.

Discounting is the process of bringing all future cost values into current value of money. It is done by accounting for the time value of money. Ideally, the value of investment increase over time by a potential percentage rate of return. The evaluation of alternative

investments paths is, therefore, evaluated compared with the theoretical return of the initial investment, if the money had been invested rather than spent.

The difference between this return and an average inflation rate (as inflation - the decline in the value of money – is also a function of time and is therefore considered when calculating real values), expressed as percentage, is called the ‘real discount rate’. Real discount rate is used for bringing future costs to present day values in LCC analysis.

The discounted value of future costs, minus future incomes (e.g., potential interest) is called Net Present Value (NPV). NPV is expressed by the following equation:

$$(1) NPV = \sum_{i=0}^n \frac{V_i}{(1+r)^n}$$

Where:

NPV = Net Present Value

n = period of analysis in years

i = Present

V_i = Cost in year i

r = Real discount rate

The value of the discount rate needs to be carefully considered, as it has an important impact on NPV (Churcher and Tse, 2016). The rate of the real discount rate should be set in accordance with the Green Book (HM Treasury and Treasury, 2011), i.e., 3.5% for the first 30 years of a building, falling to 3.0% between its 31st to 75th years.

2.2.6. Limitations of Life Cycle Studies

Stating clearly the study assumptions and limitations is an important step that contributes to the study transparency and delivery. The interpretation process of the study results should be carried at each stage of the analysis, in light of the study assumptions and limitations (ISO 14040, 2006). Though the different LCS protocols have different aims, they share most of their limitations (Bayer et al., 2010). Their outcomes are not finite and absolute but rather open to interpretation, iteration and updates.

Some LCA causes for uncertainties were discussed by Huijbregts (1998). These include model uncertainties, variability between sources, variability in input parameters and more. Hammond & Jones (2011) state that limitations are inseparable from any LCA study. In order to help in the decision making process, uncertainties must be kept at a minimum (Duda and Shaw, 1997; ISO 14040, 2006; ISO 14044, 2006). Uncertainties in LCS in buildings might be the reason of:

Study scope – Since studies vary in their scopes, boundaries and primary energy definition, conducting a meaningful comparison between results of case studies with different boundaries is very challenging (Sartori & Hestnes, 2007; Jiao et al., 2012).

Occupant behaviour and operational energy use – Occupant behaviour might have an important impact on the operational performance of buildings compared to the simulated performance, however, an accurate prediction of users behaviour and building systems operation throughout a building life cycle is unlikely (Diakaki, 2009).

Energy in use calculation – Operational energy is calculated differently in different studies. Some studies use simplified formulas while others use building thermal simulation tools. While the later are considered to be the most accurate way for predicting energy consumption in buildings, studies show that they might result in significant consumption figures when compared to actual consumption (Raslan & Davies, 2009; Maile et al., 2010; Wang et al., 2012).

Data quality – Dixit et al. (2010) state that the way embodied energy is calculated has an important impact on the results of LCA studies. The strength and weaknesses of using different embodied CO₂ calculation methods were discussed extensively in section 2.2.4. When the cost of operational energy is considered, fuel price has varied significantly in the past few decades, from around 3.5\$ (22\$ inflation adjusted), to 92\$ (105\$ inflation

adjusted) and down to around 53\$ in 2017 (Baffes et al., 2015; Statista - the statistics portal, 2018).

The Methodology – Cooper & Fava (2006) showed how the implementation of the LCA framework by different practitioners can affect LCA results. Their study has shown that LCA process is not always fully clear to practitioners, and that an integration of different methods and tools during an analysis process can lead to a lack of consistency on the evaluation of results.

It is pointed out that due to the various limitations of life cycle studies, the frameworks are not expected to predict accurate future impacts but rather to indicate which design alternative is preferred (Ashworth, 1996). And yet, to establish a model of a complete building system, it is necessary to simplify the complex processes of construction and consumption in buildings. This, however, increases the risk of oversimplifying reality and excluding valuable and important data (Gluch & Baumann, 2004).

2.3. Life Cycle Carbon Footprint (LCCF) of New and Refurbished Buildings

One main aim of this research was understanding the LCCF buildings in general, and the comparison between that of refurbished and new buildings in particular, while keeping their LCC at a minimum. As current literature (section 2.1) has shown that current literature is not sufficient to determine which design alternative is preferable, in terms of LCCF, a detailed investigation was carried, through a systematic literature review of case studies, to determine whether a preferable design alternative can be found,

It was also noticed that despite the recent increasing number of LCCF studies, an overall database of the LCCF of buildings, or a benchmark, had never been presented before. Such a benchmark database could assist practitioners in evaluating the performance of their buildings and indicate whether the analysis they carry is within a reasonable range of results. Consequently, a systematic review of case studies buildings was carried out,

presenting, for the first time, a benchmark and analysis of the LCCF of new and refurbished buildings.

This systematic literature review of case studies aims to investigate the LCCF of refurbished and new and buildings, to determine whether the environmental impact of one design alternative outperforms that of the other. In addressing this, the objectives of this study are:

- A. To collect data of the LCCF of a series of case study buildings and, for the first time, present their results.
- B. To synthesise the data and examine various factors that might contribute to the LCCF of refurbished and new buildings.
- C. To compare the LCCF of new and refurbished case study buildings.

2.3.1. Context

To address the aims of this review, a case study database was established for benchmarking purposes. The systematic review involved the interrogation of electronic databases of scientific journals available up to January 2018. These included ScienceDirect, SpringerLinks and the UCL Library journal search engine. 988 relevant papers were initially found when using defined search terms. Of these, 237 articles were omitted after filtering for duplication, relevance of titles and abstract screening. Following this, the review further applied inclusion and exclusion criteria to fulfill its aims. Only studies that contained an analysis of the LCCF performance of buildings were included, and only when this information could have been extracted and normalized to units of $\text{kgCO}_2/\text{m}^2/\text{y}$ floor area (similarly to the normalization method presented by Sartori and Hestnes, 2007 and Ramesh, et al., 2010 for the benchmarking of the Life Cycle Energy in buildings). Two parameters were defined as minimum inclusion criteria – embodied and operational CO_2 emissions – as these are the two main emission sources. Only 48 papers contained all the relevant data and could be used. These papers examined a total of 263

case study buildings from 20 countries, covering residential, office, university, industrial, hotel and hospital buildings.

It is pointed out, though, that this literature review simply compares the LCCF of refurbished and new buildings, and that the embodied CO₂ of the building elements that need to be disposed of, to enable a refurbishment or a replacement of an existing building (e.g., the CO₂ of the replaced elements in the case of a refurbishment, or the embodied CO₂ of the entire structure of an existing building in the case of a replacement) were not taken into account in none of the case studies. This is important, as the removal of existing elements are essential the realization of both refurbishments and replacements, and the removed elements might bare a significant amount embodied CO₂.

2.3.1.1. *The Case Study Stock*

To allow a cross-analysis between various design variables, whenever possible, data was collected for a range of building properties. These included life cycle energy use, the life cycle steps that had been taken into account, buildings floor area and number of stories, construction type, buildings systems, operational energy calculation methods and more. An overview of the case studies is presented in Table 2.2.

It is important to note that results were presented in different ways in the reviewed papers. While some included LCCF calculations for the whole building, others calculated it per building m² floor area. Similarly, some studies showed results for the whole life span of the building, while others presented only annual emissions. Finally, results were graphically illustrated across papers in various formats, including tables and graphs.

To enable a true comparison across the case study database, this study normalized their outputs to a unified comparable metric. In most parts of the analysis, results were normalised to an assumed kgCO₂/60 years life span per 1m² floor area, following a guidance by the BRE – Building Research Establishment – assumed life span for buildings (BRE, 2009b) . When only graphs had been presented, data was manually extracted from

them. The use of this process may potentially lead to the introduction of minor inaccuracies and consequent uncertainties.

Whereas LCE review papers have referred to primary energy values (Sartori & Hestnes, 2007; Ramesh et al., 2010), most LCCF studies did not make this distinction. However, Sartori & Hestnes (2007) note that Embodied Energy values of the most common LCA practices and databases refer to primary energy values. Also, when converting operational energy values to CO_{2e}, conversion factors take into account losses caused by the production and delivery processes, and therefore represent primary CO_{2e} values too (SimaPro UK, 2015). For these reasons, this study assumes that full LCCF studies describe CO_{2e} footprint due to primary energy consumption.

Number of papers	48	Country	Number of papers
Number of case studies	263	UK, Sweden	6
Of which		China	5
New	218	Finland	4
Refurbished	45	USA, Korea, Italy	3
Residential	177	Spain, Australia, Canada,	2
Office	34	Germany	
University	34	Norway, Thailand, Belgium,	1
Industrial	15	Bahrain, Portugal,	
Hotel	2	Singapore, Puerto Rico,	
Hospital	1	Japan, Austria	
		Reviewed papers location (Some papers reviewed more than one location)	

Table 2.2: Scope of the systematic literature review

2.3.2. Limitations and Uncertainties

In analysing the case study stock, some limitations that might influence the analysis results have been considered. Although the nature of a systematic literature review minimises these, limitations nonetheless still exist. In this review, the following uncertainties can be highlighted:

- It is acknowledged that the case studies in this review differ in their location and that their operational source energy and its CO_{2e} emissions differ.
- Similarly, embodied CO_{2e} emissions of comparable buildings across the stock might vary because of different production and construction processes.

- Various databases or embodied CO_{2e} calculation methods were used in the studies analysed.
- A number of tools were also used for the calculation of operational energy consumption (Table 2.3), and for the energy/CO_{2e} emissions conversion factors.

Differences in the protocols used by the various studies for LCCF calculations, and the various stages in the buildings life cycle (Table 2.4) may potentially have some impact on results too, and it is noted that studies may have used different LCA scopes and assumptions in their buildings.

Despite the differences between the case studies across the database, this review is designed to provide researchers and practitioners with an initial benchmark of reasonable and sensible LCCF results, and a comparison between the LCCF of refurbished and new buildings.

Operational Energy calculation method	Number of papers	Number of buildings
Dynamic simulations	19	125
Static simulations	4	22
Measured (bills/smart meters)	5	8
Estimated	3	14
Manual calculations	3	8
Mixed	2	5

Table 2.3: Operational energy calculation methods, used for the calculation of operational CO_{2e} emissions (of the papers that mentioned the method they have used).

Life Cycle Stage	Number of papers	Number of buildings
Transport	26	117
Construction	29	145
Maintenance	33	163
End of Life	27	154
Recycling	14	63

Table 2.4: Number of papers that presented data about the different life cycle steps (out of a total of 48 papers and 263 buildings).

Life Cycle Stage	Gross	Heated (a)	Net (b)	Other (c)
Papers	15	11	4	15
Buildings	85	83	25	64

Table 2.5: Case study buildings floor area (of the papers that mentioned the metric they have used). (a) Included expressions such as: “Heated floor area” or “Habitable space”. (b) Included expressions such as: “Net floor area”, “Useable area” or “Letable area”. (c) Included expressions such as: “Building area”, “Floor area”, “Overall area” or included no description.

Embodied CO _{2e} calculation	Number of papers	Number of buildings
Local material database (a)	14	68
Independent calculations / relying on academic papers	11	68
Mixed methods (b)	9	35
LCA calculation tools (c)	7	67
EPD	4	17
No description	3	8

Table 2.6: Embodied CO_{2e} calculation method. (a) Databases such as Bath-ICE, Athena, PCT ITEC and others. (b) A combination of databases, EPD and independent calculations. (c) tools such as Gabi, SimaPro and Eco-Invent.

2.3.3. Findings

2.3.3.1. LCCF Results

The analysis of the database showed that more than 90% of the examined buildings emitted less than 8,000 kgCO₂/m² throughout the various buildings life span. Generally, buildings with high operations-related CO₂ emission profiles (university, commercial, hospital and hotel buildings) had significantly higher LCCF values (4,980 kgCO₂/m²/y on average, 3,820 stv) than low profile ones (residential buildings - 2,310 kgCO₂/m²/y on average and 1,789 stv).

Figure 2.6 shows the results after normalisation to an expected 60-year life span and a breakdown according to each life cycle step (the breakdown data were available for 183 cases only). Results show that embodied CO₂ emissions account for anything between 3% and 77% of the overall LCCF (Average = 24), compared with Sartori and Hestnes (2007) and Ramesh et al. (2010), who found that embodied energy ranged between 10–20% and 2–46%, respectively (their studies focused on embodied energy rather than embodied CO₂).

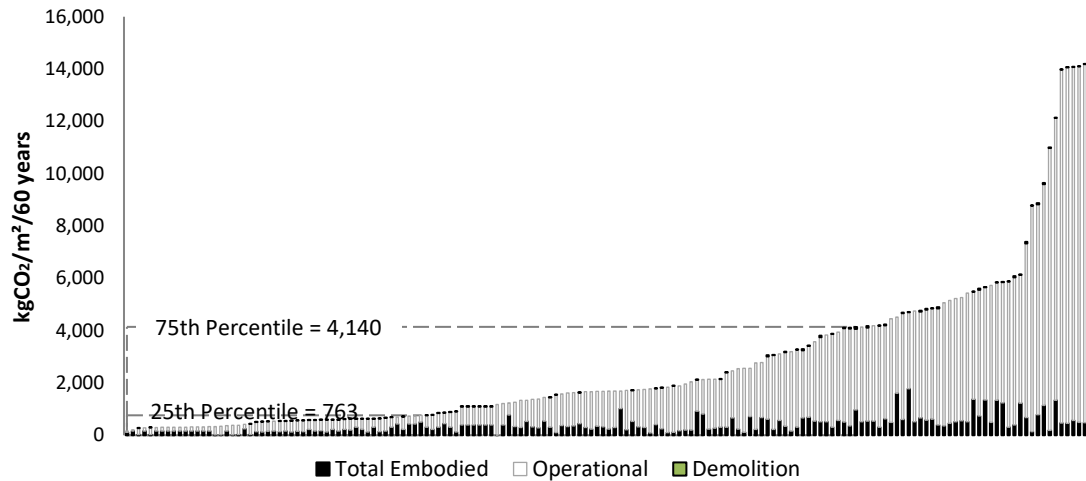


Figure 2.6: LCCF results for 60 years, all case studies.

Operations-related CO₂ accounted for between 23% and 97% of total LCCF (75% average). Case studies that included calculations of CO₂ emissions due to demolition works (46 case studies) showed that it accounted for between 0.1% and 2.9% of the total building LCCF (Average = 1.0%).

While CO₂ and energy are frequently used as different metrics for measuring building performance, Figure 2.7 surprisingly indicates that there is a weak relationship between LCCF and the life cycle energy consumption of the examined case studies (R Value-0.25). This weak relationship is attributed to the different levels of CO₂ per unit of energy emitted by different fuels, and to the varied fuel types and to the energy consumption intensity during the different buildings life stages.

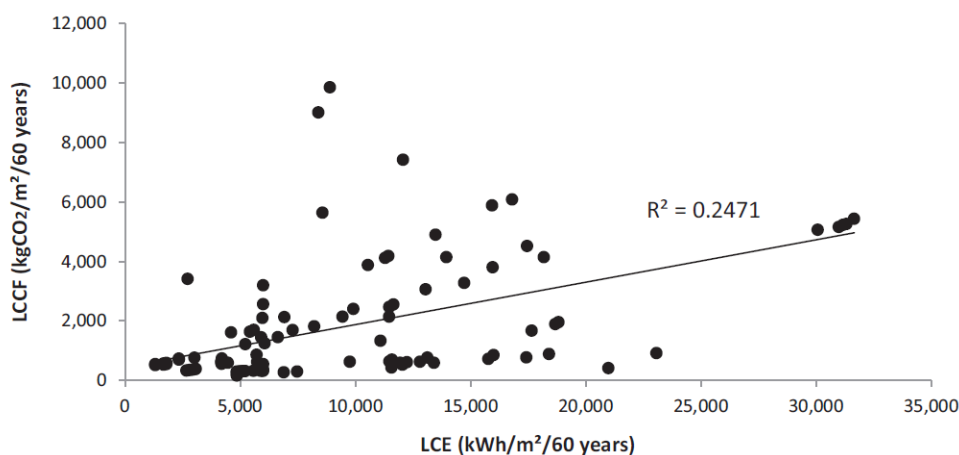


Figure 2.7: The relationship between LCCF and LCE

2.3.3.2. Influential LCCF Environmental and Design-related Factors

To better understand the relationship between LCCF and various environmental and design-related factors, a further analysis was conducted. The analysis highlighted the weak relationship between LCCF ($\text{kgCO}_2/\text{m}^2/60$ years) and the overall floor area of case studies ($R^2 = 0.09$) or number of stories ($R^2 = 0.05$). On the other hand, it is noted that buildings that used district heating technology to deliver space heating – a major source of energy consumption - usually resulted in an overall low LCCF. Also, in examining the relationship between climate and overall LCCF, the study matched LCCF results with climate types (tropical, dry, moderate, continental and polar) but found no distinctive relationship between LCCF and climate. It is suggested that this can be attributed to the different manufacturing techniques, fuels and heating/cooling technologies used in the different countries rather than to climate. Further research, however, is needed to further explore the relationship between climate and LCCF, as available data is limited.

2.3.3.3. New/Refurbished Buildings

In this section, a comparison between the LCCF of refurbished and new buildings was carried out. Although the study adopted the 60 year assumed life span from the BRE Green Guide (BRE, 2009b), some refurbishment LCCF studies conducted a 50 year analysis. Since it is impossible to draw the annual emissions in these case studies and calculate their emissions for 60 years (the relevant data was not available), the results in this section has been normalized to an assumed 50-year life span.

Figure 2.8 presents the LCCF of refurbished buildings as compared to that of new ones, across all buildings types. Results show that while the LCCF values of refurbished buildings are spread across the graph, with both very high and very low values, more refurbished buildings fall in the higher 50 percentiles. It is noted, however, that some refurbishments still achieved better performance than new built. It is also important to note that most studies did not describe the level of refurbishment that was carried out.

To minimise the potential impact of building type and usage profile on results (university and commercial buildings, for example, are typically more operational-energy-intensive than residential buildings), a further investigation was conducted on residential buildings only – the building type with the largest sample in this review.

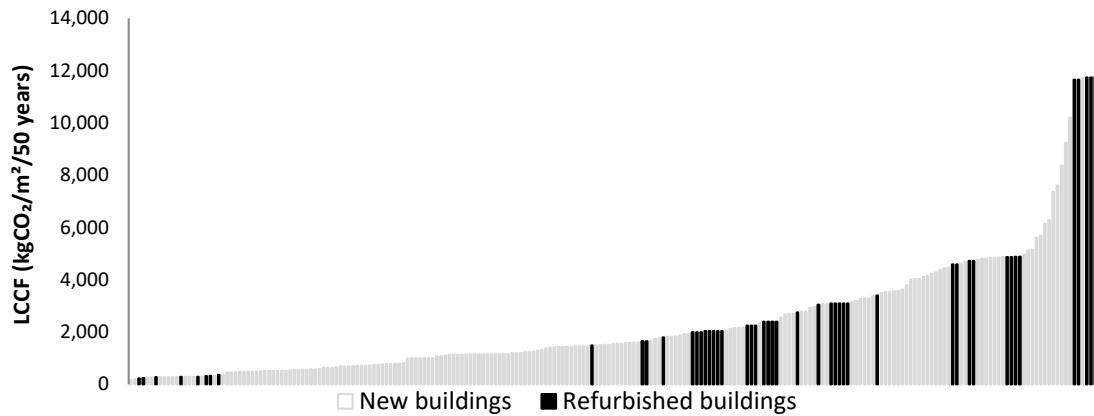


Figure 2.8: New/Refurbished buildings – all buildings types LCCF (kgCO₂/m²) for 50 years.

When examining refurbished and new residential buildings in the UK and Ireland – cases with geographic proximity and similar climate and construction materials (Figure 2.9) – refurbished buildings seem to have a better performance than new ones – with an average LCCF of 3,500 (new) and 2,250 (refurbished) kgCO₂/m²/50 years (n1=28, n2=26, p<0.05). While this trend is statistically significant, some new buildings still showed a better performance than the best refurbishments. It is yet hard to determine which alternative can be considered as better.

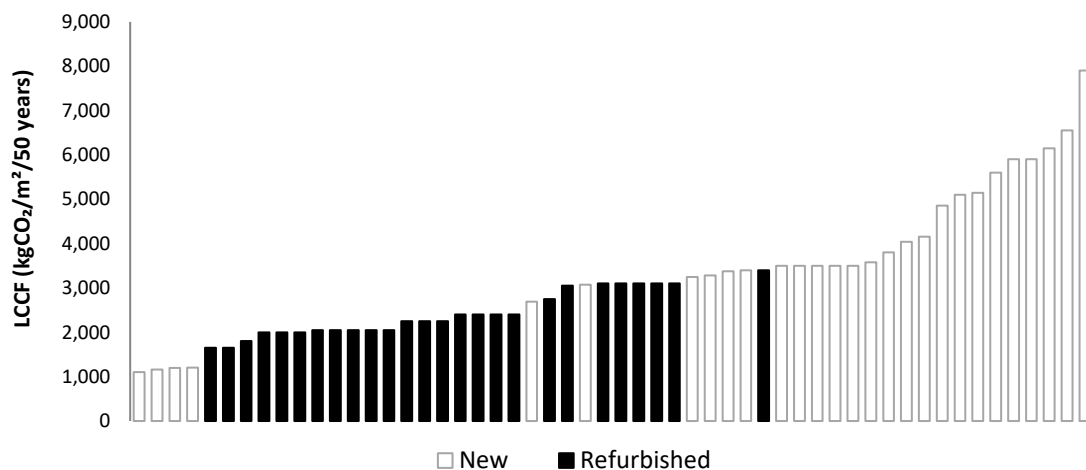


Figure 2.9: UK and Ireland- New / Refurbished buildings LCCF (kgCO₂/m²) for 50 years

The systematic literature review also included an analysis of other findings, such as: embodied CO₂ calculation methods, operational energy consumption calculation approach, typical life cycle stages etc. Further details, can be found at “The life cycle carbon footprint of refurbished and new buildings – A systematic review of case studies” (Schwartz et.al., 2018).

2.4. Computational Analysis Techniques

2.4.1. Parametric Modelling

Currently available simulation tools enable the analysis of building thermal performance through a relatively simple modelling process that largely involves a single model that is built and assessed solely based on user-generated building design inputs. Design teams and clients and both benefit from performance-based design, as it can assist in creating better, more environmentally aware and cost effective environments (Spekkink, 2005). Thermal simulation analysis is, however, often limited to examining specific and rather limited aspects of buildings properties.

Many building design optimisation problems are in fact 'parametric combinatorial problems'– problems to which solutions are the result of a combination of pre-defined conditions – as described in Figure 2.10 (Yang & Deb, 2010). Parametric modelling is the process of exploring different design alternatives and finding the combination of parameters that will leads to the design with the best performance (Panczak & Cullimore, 2000).

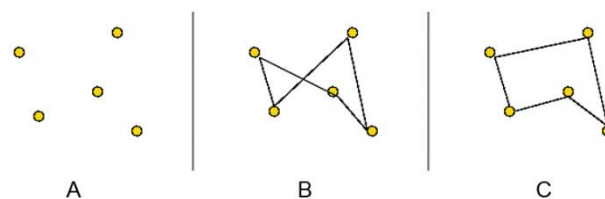


Figure 2.10. The Travelling Salesman Problem – a parametric combinatorial problem example.

The task in this example is to pass through all the yellow dots (A) in the shortest possible way. A possible solution is the sum of the distances of a specific combination. (B) is one non-optimal solution. (C) is the optimal, shortest solution.

In combinatorial analysis problems, model properties (also denoted as 'parameters') have a cause-and-effect relationship between input variables and output results: Each change in an input variable has an effect on the overall outcome. Combinatorial problems have a finite, sometimes very large, number of optional solutions, which is referred to as the 'Search Space' or 'Solution Space' (Blum & Roli, 2003). In such analysis studies, model properties are modified and updated in an iterative manner: new models are created – often hundreds or thousands (Naboni et al., 2013) – and their performance is evaluated.

Where multiple objectives are involved in optimisation, search mechanism that attempt to find the problem's pareto front – a set of solutions that are not dominated by any other solution – are often used. Figure 2.11 illustrates the pareto front and dominance concepts. The non-linear nature of complex engineering design problems, however, may result with more than one acceptable solution to a problem, or with a 'multi-dimensional' result space (Figure 2.12). Combinations that lead to possible solutions are referred to as 'locally optimal' solutions, while the best possible solution is considered as the 'globally optimal' solution (Yang & Deb, 2010). When searching for globally optimal solutions, some search algorithm might get "trapped" in a confined locally optimal area within the search space. This occurs when no better solutions exists in their immediate proximity, while other optimal solutions might exist further away from each other (Rakkwamsu *et al.*, 2012).

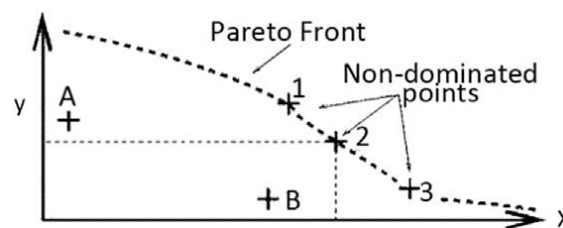


Figure 2.11: Pareto front. Source: Poli et al. (2008)(adapted from Langdon, 1998).

A pareto solution dominates another when it has as good solutions as the second one for all objectives, and at least one solution where it is better (Blum and Roli, 2003). In this case, individual 'B' dominates 'A' along the x axis while individual 'A' dominates 'B' along the y axis. They dominate each other on different objectives. On the other hand, no individual dominates '2' in both axes.

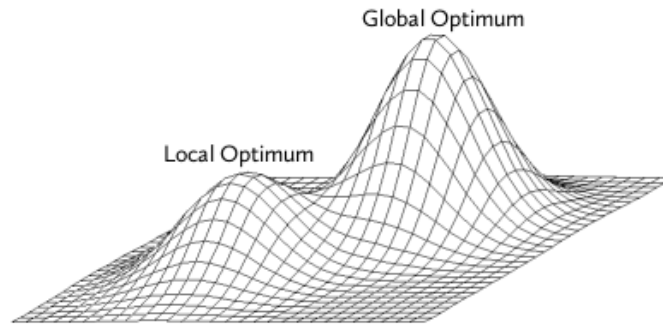


Figure 2.12: Multidimensional search space with global and local optimums. (Image from: <http://www.doxsey.net/blog/too-practically-minded-to-be-of-any-theological-good/>)

Once the parametric procedure is set out, optimal solutions can be found using various strategies, e.g.: brute force, sensitivity analysis or various optimisation methods.

Brute Force: A simple approach, in which the optimal solution is found by performing iterative modeling updates, to cover each and every possible solution in the search space, to ensure that the best solution is found.

While using a brute force approach would lead to the best solution, the iterative search throughout the whole search space can be extremely time and resource consuming. This is especially challenging when the user is needs to examine a wide range of alternatives, or when the problem has a large number of possible solutions, (Calleja Rodríguez et al., 2013; Nguyen et al., 2014; Hanna et al., 2010). Therefore, for complex parametric problems, advanced computational searching techniques are often used, also known as 'Optimisation'.

Mathematical Optimisation: In mathematical programming, optimisation is the process of finding the best feasible solution to a problem out of all other possible alternatives (The nature of mathematical Programming, 2014). Computational optimisation techniques have been developed and used for various purposes since the 1960's (Yang, 2011), while

in the built environment, they have been more widely used only since the late 2000's (Nguyen et al., 2014).

Optimisation algorithms are often used in more complex parametric problems: where the search space is too big or when time or computational resources are scarce. These algorithms use advanced stochastic search mechanisms in which some level of randomness is allowed to enhance the search process. This enables the search mechanism to both create a general description of the search space and avoid 'local optimum', by occasionally "pushing" the search mechanism outside local traps (Erol & Eksin, 2006). It is pointed out that while randomness can save computing time and increase the levels of certainty, there is no guarantee that an absolute optimal solution will actually be found (Pappas et al., 2004).

Figure 2.13 illustrates a step-by-step execution of a Genetic Algorithm optimisation. The optimisation starts by generating a first generation of thermal models, which are then go through a simulation (a). The models are then ranked by their performance - LCCF and LCC in the case of this research (b). Following this, some of the best-performing models are then selected and undergo various manipulations – inspired by the theory of evolution (breed, mutation and cross-over), to create a second generation of thermal models (c). The procedure then goes back to the simulation and ranking stage (b). This process (model generation -> simulation and ranking -> selection, breed and mutation) is then repeated, until the best solutions are found, or until a maximum number of generations is reached.

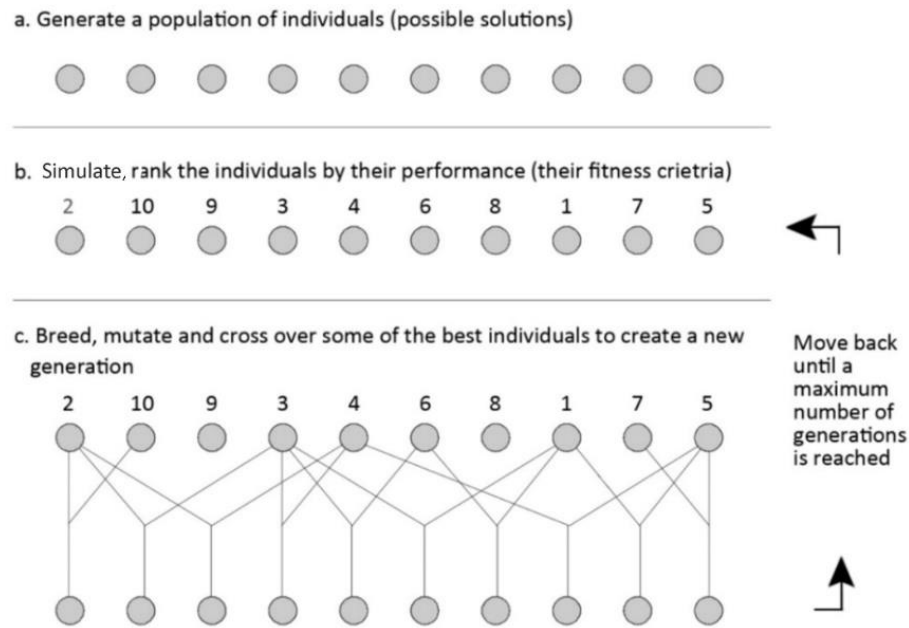


Figure 2.13: The step-by-step execution of Genetic Algorithms optimisation

2.4.2. Generative Spatial Design Programming

Generative design is a term used to describe the automatisation of the design process. Unlike traditional design – which focuses on the design result, or the ‘end point’ – the focus in generative design is the setting out of procedural rules, constraints and flows that define the automation of the design process, rather than the end product itself.

In the built environment, generative design is often referred to the attempts to harness computational techniques to automate the process of building design or urban spaces (also referred to as ‘the Space Allocation Problem’). Put simply, the space allocation problem aims to find the layout that satisfies certain spatial criteria (e.g., minimal distance, maximum compactness etc.), given a set of spaces or activities, and their desired adjacencies. The space allocation problem is often considered to be of the most challenging and difficult area of computer-aided design (Kalay, 2004).

Various space allocation techniques have been developed since the 1970’s (Merrell et al., 2010). Important work was published by (Galle, 1981), (Shaviv & Gali, 1974) and Hillier et al. (1976), who developed a unique design approach using ‘shape grammars’ for

space configuration – a sequence of rules and condition for spatial division. The space allocation problem has gained a revived attention since the 2000's, with the emergence of computers with improved capabilities and the development of advanced computational algorithms. This, coupled with demand from emergent market (such as the gaming industry) for computer engines with capabilities to automatically generate different buildings, led to further of automatic generative design.

The state-of-the-art generative design techniques can be roughly divided into the two following categories:

A. Simple Building Shape Generation: a "Top - Down" Approach

Most applications that used automatic shape generators, have used simple geometric manipulations to buildings shapes, as described in Figure 2.14 (Basbagill et al., 2014, Bichiou & Krarti, 2011, Tuhus-Dubrow & Krarti 2010). In these cases, whole floors were considered to be empty 'shells' – individuals thermal zone – where only their perimeter and footprint could be modified, while maintaining the same overall floor area. Internal partitions and spatial arrangements were not generated.

Another common algorithm for space allocation is the 'tree-map diagram' (Duarte, 2001; Kalay, 2004; Marson & Musse, 2010), as presented in Figure 2.15. Tree-map is a tiling algorithm – a procedure for representing data, which is the result of a hierarchical, tree-structured procedure for sub-dividing a given polygon. The basic principle behind the tree-map procedure is the division of space, in a proportional manner: i.e., a rectangle is divided into sub-rectangles, that can be further divided into smaller rectangles, based on the dimension they have been given. The sub-division is often carried in an alternate horizontal-vertical manner, so that a minimal aspect ratio is achieved. While tree-map diagrams can be used for space division for architectural design, their main limitation is the fact that they can only be used in convex rectangular polygons and cannot accommodate any non-convex floor-plan contours, which are very common in buildings.

Limited attempts to use tree-map in more flexible boundaries were developed: More realistic floor plans were generated by introducing corridors to the Tree-map algorithm (Marson & Musse, 2010), or a spiral-based tree-map (Shekhawat, 2017) that was used to divide a 'plus' shape polygon. The inherent limitation of the 'top-down' approach - the bounding to a specific given shape - was, however, yet to be solved.

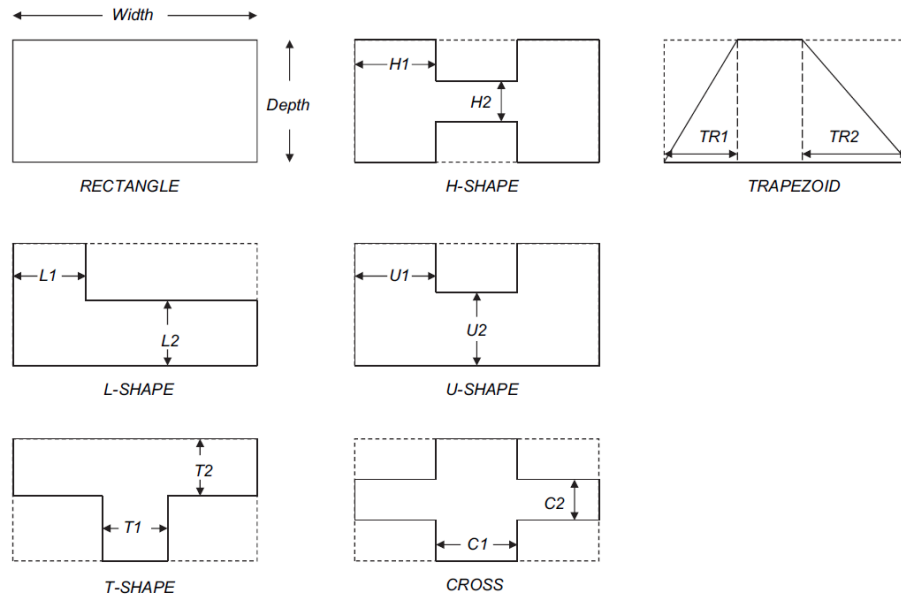


Figure 2.14: Contour manipulation (Tuhus-Dubrow & Krarti, 2010).

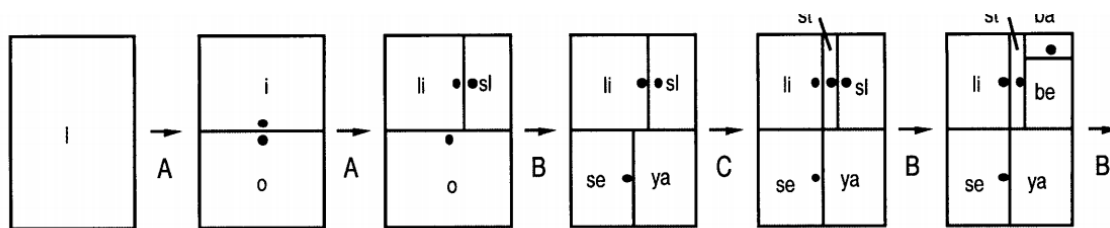


Figure 2.15: Shape grammar and sub-division of pre-defines spaces (Duarte, 2001).

B. Complex Building Geometry Generation: a "Bottom – Up" Approach

While the “top – down” examples accounted for simple envelope geometric modifications, they did not perform any change in the distribution of spaces of different use within the building.

This approach was introduced by Caldas (2008), who applied simple geometric manipulations on an initial model of a museum buildings, to generate different design alternatives. This was undertaken by defining a basic layout of four equally-sized adjacent rectangular spaces and changing their width and length parameters – similarly to the method used by Tuhus-Dubrow & Krarti (2010). Though the strict initial layout design (as illustrated in Figure 2.16) this method resulted in a relatively large variation of different shaped buildings. Still, the generated layouts were restricted to a fixed spatial arrangement (each distribution of thermal zones was identical in all layouts) and to the same adjacencies throughout.

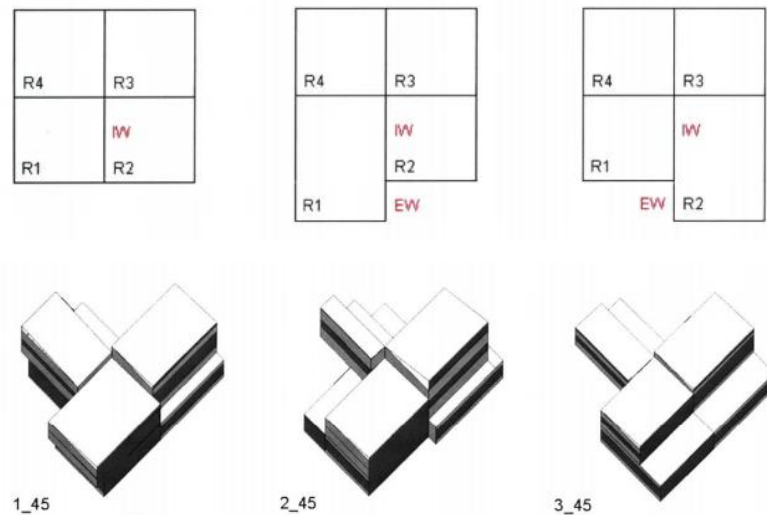


Figure 2.16: The basic starting-point layout in Caldas (2001), and some of its parametric variations

With the incorporation of advanced computational techniques (heuristics, Evolutionary Algorithms (EA) and Artificial Intelligence (AI)) that have been rapidly adopted since the early 2000's, 'bottom-up' generative design techniques have shown increasing promising results.

(Chatzikonstantinou, 2014) applied a shape grammar-type algorithm, where rooms were randomly distributed across a plot based on an initial proximity matrix. However, as the proposed framework could not take room dimensions as an input parameter - the outcome was of buildings with unrealistic room size.

Other studies introduced evolutionary algorithms coupled with an agent-based spring-system-like algorithm (Guo & Li, 2017), to enable the generation of a compact multi-story building. While this approach proved to be able to deal with the allocation of a large number of rooms (up to 40) – the output could generate un-realistic layouts, such as spaces with no external walls (or more importantly – spaces with no window) or complex geometries with no vertical connection to the ground – which might add practical structural complexities.

The most advanced approach for spatial arrangement problem introduces AI in the form of Bayesian Network (Merrell et al., 2010). In their study, Merrell et.al trained a Bayesian Network based on 120 architectural layouts of residential buildings, and successfully managed to generate realistic single-storey and double-storey building. While this approach has proved to be successful, it suffers from the main limitation of supervised AI algorithms – the outcome is always based on the initial training set, and therefore, no ‘new’ or ‘innovative’ designs will be generated. Instead, the resulted buildings will always have certain similarities (in proximities / shape or functionalities) to the initial batch of buildings from which the AI was trained.

This review concludes that while current attempts were successful in developing a method for the generation of simplistic building designs, spatial arrangement generation is still a challenge, as previous spatial arrangement algorithms have resulted with limited outcomes. The application of a realistic generative design application is still lacking.

2.5. The Application of Computational Techniques in the Built Environment

2.5.1. The use of Optimisation Algorithms

A great range of optimisation algorithms have been developed in recent years. Each has a different approach towards the optimisation process, which might result in a slightly different application. Table 2.7 shows a brief summary of some of the most commonly used optimisation algorithms in the built environment. Covering more than 200 building

optimisation studies, Nguyen et al. (2014) show that Genetic Algorithms (GA) is the most widely used optimisation algorithm across the discipline. The review also shows that among the different GA codes, Non-Sorting Genetic Algorithms II (NSGA-II) can achieve a more accurate solution, faster and more efficiently than other GA's. The review also points out that optimisation frameworks have been used in the built environment primarily in two main fields: structural optimisation and building performance optimisation.

A description of some of the most widely used Optimisation Algorithms

Name	Best for	Description	Type	Use in the built environment
Direct Search (Hill Climbing)	Continuous search space (local optimums only) (Powell, 1973)	Developed in the late 1950's, Direct Search is one of the simplest and reliable existing search algorithm (Yang, 2011). At its core is the iterative change of input parameters, one variable at a time, and the constant search for combinations that produce improved performance. When no improvements appear, the parameters' increment magnitude is halved, until the change-magnitude is sufficiently small (Kolda et al. 2003, Pardo, 2011).	Deterministic	<ul style="list-style-type: none"> • Spatial arrangement (Assiego De Larriva et al., 2014), • HVAC system optimisation (Wright 1985)
Simulated Annealing	Complex search space (finding global optimums) (Yang, 2011).	<p>Inspired by the metal annealing processes, the method starts with a random solution to a problem. In each iteration, the algorithm adjusts the examined parameters by small amounts to search neighbouring solutions for better performance.</p> <p>Contrary to Direct Search, Simulated Annealing does accept some non-optimal or even worse solutions than previous ones, in order to increase the chances of escaping local optimums. This, however, is a probabilistic process: the algorithm decreases the probability of searching around non-optimal solutions as it advances.</p>	Probabilistic	<ul style="list-style-type: none"> • Minimising concrete frames' environmental impacts (Paya-Zaforteza et al. 2009) • Minimising concrete frames cost (Paya et al., 2008) • Acoustics Performances (Cobo et al., 2015) • Building energy-use management (Velik and Nicolay, 2015)
Ant Colony	Finding the shortest paths through graphs	<p>Inspired by the way ants find optimal paths between food and their colony (Colorni, Dorigo and Maniezzo, 1991): While searching for food, ants randomly wander around their colony. Once a food source is found they lay pheromone on the ground on their way back to the nest. When other ants bump into this path, they follow it and lay pheromone on the ground too, strengthening a positive feedback between the food source and the colony. This way, short paths are more pheromone-intensive than long ones.</p>	Probabilistic	<ul style="list-style-type: none"> • Load distribution and structural optimisation (Ali and Belal, 2007; Ghazavi and Bonab, 2011)
Bee Algorithm	Complex search space (global optimums)	<p>Based on the pattern in which bees find food source and communicate their locations. When a bee colony forages, a small group of bees is sent to scout, randomly around the hive. Once food is found, the scouts communicate its location. Other bees then join the scouts to search around the initial source and expand the search area to find its exact location. If the patch is rich, more bees will go back, attracting even more bees to follow. This way, rich food sources are visited more frequently, increasing the probability for finding the patch's exact location. Similarly, Bee Algorithm generates random solutions (scouts/agents). The scouts with the best solutions then attract more agents to use similar input combinations. Within local optimums, agents randomly sample solutions. If a better solution is found – its rank will be updated accordingly. Otherwise – the search space around the original solution will slowly shrink, until an absolute globally optimal solution is found</p>	Probabilistic	

Particle Swarm Optimisation	Complex search space (global optimums)	<p>Based on the movement patterns of fish or bird swarms move (Yang, 2011): They move is determined both by their swarm leader and by their closest neighbours.</p> <p>The algorithm's search process starts with a random sample of results (agents). Each agent in the swarm is attracted to two different forces: a deterministic force and a stochastic one.</p> <p>The deterministic force is a combination of the agent's closest optimal solution (or, the best solution that has the most similar combination of input parameters) and to the overall optimal solution (the combination of input parameters that resulted with the best performance so far). This combination enables each particle to have the ability to move in a somewhat random manner and escape local optimums.</p>	Both Deterministic and Probabilistic	
Harmony Search	Complex search space (global optimums)	<p>Based on the way musicians search for the most harmonious combination of notes (Yang, 2009).</p> <p>In the first step of the algorithm, a random set of solutions is generated and ranked from 'most harmonious' (best solutions) to 'least harmonious' (worst ones).</p> <p>Next, 'improvisation' occurs: new solutions are generated based on the parameters previously used. If any of the new solutions is better than any of the existing ones – they are replaced (Geem, Kim and Loganathan, 2001; Yang, 2009).</p>	Probabilistic	<ul style="list-style-type: none"> • structural optimisation - (Akin and Saka, 2015) • Locating optimal structural dampers (Amini and Ghaderi, 2013)
Genetic Algorithms	Complex search space (global optimums)	<p>GA is based on the processes of natural selection and evolution. It is the most commonly used optimisation methods in the research of the built environment, (Nguyen et al. 2014) and is regarded to be most suitable for problems with large number of possible solutions (Hanna et al., 2010).</p> <p>GA starts by generating a random set ('population') of possible solutions. Results are evaluated and solutions are compared to a pre-determined target ('fitness criteria') and ranked accordingly. Based on principles inspired by evolution (breeding and crossover), GA then generates a set of new solutions, based on some of the best, or 'fittest' individuals. In order to escape local optimums, the algorithm uses mutation – a random property in some of the new individuals.</p>	Probabilistic	

Table 2.7: Summary of the most common optimisation algorithms in the built environment

2.5.2. The Application of Optimisation in the Built Environment

Computational optimisation tools are currently used for various purposes in the built environment, including structural stability analysis, load distribution calculations, energy consumption evaluation, minimising environmental impacts or improve thermal comfort (Garber, 2009).

2.5.2.1. Structural Systems Optimisation

The focus of structural optimisation studies is on structural stability and load analysis. Therefore, structural optimisation optimisations often couple optimisation methods with load and stress calculations such as Finite Element Analysis (FEA) (El Semelawy et al., 2012).

Most structural optimisation studies focus on minimising weight, cost or embodied energy – all related to amount of material in the structure. For such purpose, single objective algorithms is often used. This was the case in Chung et al. (1994) and Sahab et al. (2005), who used this mechanism for the optimisation of a concrete flat slab building to minimise the overall strcture cost. Martí & González-Vidosá (2010) examined a complex system and a great number of design parameters – sixty design variables – to economically optimise the design of a concrete bridge, and Yeo & Gabbai (2011) used environmental impacts as an objective for structural optimisation, when optimising the reinforcements of concrete structures. The study reached a 10% reduction in the structure`s embodied energy, compared to the original design.

When more complex design targets are set, multi-objective optimisation methods can be used: El Semelawy et al. (2012) applied multi objective optimisation when searching for the optimal design of a concrete slab, taking both cost and a number of design constrains as objective functions. The study compared various optimisation algorithms and concluded that Multi-objective GA had the best performance.

2.5.2.2. Building Environmental Performance Optimisation

Another major field in which optimisation is used in is building environmental performance. One major component in these studies is the use of building performance evaluation tools. The environmental performance of buildings is usually measured by predicted energy use, predicted energy cost or its associated CO₂ emissions. To evaluate buildings energy performance, three main methods can be used:

- A. Hand calculation, based on simplified representation of the building, its systems and use (Hasan, 1999; Gustafsson, 2000).
- B. Simplified Building Simulation Models (SBEM), tools that calculate aggregated energy consumption averages. These include packages such as PHPP (PassivHaus Planning Protocol) and SAP (Standard Assessment Method) Ostermeyer et al., 2013).
- C. Dynamic Simulation Models (DSM) – tools that can calculate hourly energy consumption in specific rooms within the building.

Figure 2.17 shows the use of thermal simulation tools in building optimisation studies (Nguyen et al., 2014).

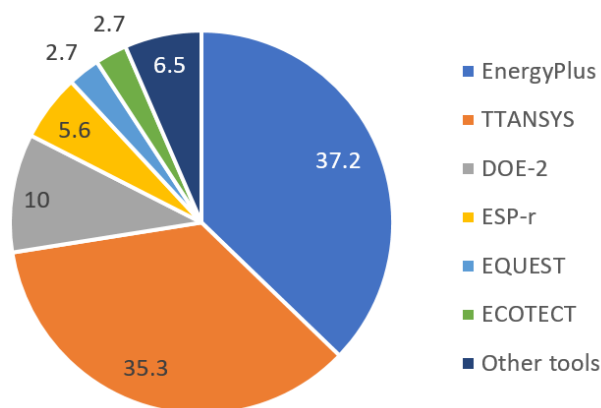


Figure 2.17: The use of thermal simulation tools in building optimisation studies, (Adapted from: Nguyen et al., 2014)

Building performance optimisation studies have used optimisation algorithms for various purposes:

HVAC Systems Optimisation - One of the most common uses of optimisation techniques is HVAC system optimisation, as shown by Congradac & Kulic (2009) and Bichiou & Krarti (2011), who compared Genetic Algorithms (GA) to other optimisation algorithms, and showed how it could be used for optimising the operation of an HVAC system, in order to minimise the overall energy consumption of a case study building and its life cycle costs. Wright et al. (2002) and Nassif et al. (2005), applied multi objective GA on the design and control of an HVAC system, to reduce case study buildings energy consumption, while maximizing indoor comfort levels.

Building Envelope Optimisation – Another common use for optimisation algorithms is the improvement of buildings environmental performance by the search for optimal envelop design: Islam et al. (2014) used a multi-objective optimisation algorithm to find the optimal wall build-ups of a typical Australian house, aiming to reduce its environmental impacts and cost. Hasan et al. (2008) applied GA on the optimisation of wall build-ups and windows U-Values of a case study building, to minimise its life cycle cost, and validated results by comparing them to a Brute Force analysis.

Life Cycle Performance as an Objective Function – A relatively new performance objective, life cycle performance has become a more common as an optimisation objective. Several studies have coupled optimisation algorithms with life cycle analysis methods to minimise building's LCCF (Life Cycle Carbon Footprint), LCC (Life Cycle Cost) or Life Cycle Energy (LCE).

Hasan et al. (2008) have used a single objective GA for the minimisation of the LCC of a detached residential building and achieved between 23-49% cost reductions. Examining a number of optimisation scenarios, in which between 4 to 10 energy efficiency measures could be used, Ihm & Krarti (2012) have optimised the design of a two-story residential

building in Tunisia in terms of LCC. The study also showed that using optimisation algorithm saved more than 99% CPU time compared to the brute-force alternative.

Multi Objective optimisation techniques have also been used in life cycle performance optimisation studies: Hamdy et al. (2011), have applied multi objective optimisation on a residential building buildups and HVAC system, and achieved around 30% reduction in both operational CO₂ emissions and embodied cost, compared to an initial design. Alaidroos & Krarti (2015) have reached up to 40% cost savings when using a multi objective optimisation on a case study building's envelope in Saudi Arabia (validated by brute force analysis). Fesanghary et al. (2012) applied a multi objective Harmony Search on the buildups of a residential building case study, in order to minimise its LCCF and LCC and resulted with a range of Pareto-optimal designs with various combinations of buildups and insulation thicknesses. Lastly, Islam et al. (2014) have successfully used optimisation algorithms to minimise five different objectives in a case study building in Australia. These included energy consumption, LCCF, cost, water use and solid waste.

Refurbishment Optimisation – Only a handful of studies have applied optimisation on the refurbishment of existing buildings: Gustafsson (2000), one of the first to use optimisation algorithms when examining life cycle refurbishment of buildings, applied a single objective optimisation on the refurbishments HVAC systems, and managed to minimise their LCC. Bojić et al. (2014) have examined various refurbishment scenarios and searched for the optimal thermal insulation, in term of life cycle energy consumption, and Han et al. (2013), have optimised building envelop and HVAC systems of a refurbishment of an office building case study.

Some studies focused on more sophisticated mechanisms in optimising the performance of refurbishments. Ostermeyer et al. (2013) have coupled a multi-criteria optimisation with a static thermal simulation tool to find optimal refurbishment designs in terms of cost and environmental impacts. The study focused on the applicability of the method,

and showed that it is possible to find favorable design solution by using optimisation methods and static simulation tools. Wang et al. (2014) used multi-objective optimisation algorithms to minimise both the LCC and the life cycle operational energy of a refurbished case study building, and managed to reach around 10% savings, and Chantrelle et al. (2011) used a multi-objective GA to optimise the renovation of a school building envelope, to minimise its heating and cooling demands.

2.5.3. Coupling Optimisation Algorithms and Generative Design

Though the use of optimisation framework in the research of build environment is becoming more common, existing building optimisation applications are still relatively difficult for use. This makes the integration of external simulation and analysis tools, such as thermal simulations, generative design or statistical analysis application, even more challenging.

Some studies improved various aspects of buildings performance by searching for optimal building shape. These might involve the modification of both the buildings thermal properties, but also their geometrical ones. Alaidroos & Krarti (2015), optimised not only the envelope buildups of a residential case-study building, but also some basic geometrical properties to the envelope, such as its window-to-wall ratio and windows overhang length. While most available optimisation tools enable the modification of non-geometric building properties (U-Values, orientation, schedules etc.), the modification of geometric building properties can result with a further improvement to the performance of buildings.

Wang et al. (2015) used parametric simulation to examine the impact of building shape on the indoor thermal comfort in residential buildings. The study, however, used a simplified approach towards the building shape, which was only represented as the ratio between the building surface area to its volume. In another study, Geletka & Sedláková (2011) conducted a parametric analysis to examine how building geometries can affect

energy consumption. The 'shape' parameter in the study could only be randomly picked out of a series of pre-designed basic building shapes, rather than be used in an optimisation procedure.

Only a few studies addressed the challenging optimisation and automated generation of spatial design: Tuhus-Dubrow & Krarti (2010) and Bichiou & Krarti (2011) have used the "Top-Down" generative design approach (as described in section 2.4.2), and coupled a parametric manipulation of pre-designed basic buildings contours (rectangle, L-shape, T-shape, H-shape and others) with optimisation algorithms to minimise their overall performance by modify the edges and proportions of the different building footprints. As expected, both studies concluded that the buildings that had the smallest aspect ratio and surface area – consistently resulted with the best performance.

Caldas (2008) presented Gene_Arch – an evolution-based generative design system that uses a multi-objective optimisation, coupled with DOE-2, for energy consumption calculations. Caldas has shown how Gene-Arch can be used for generating optimal buildings that both minimise energy consumption and maximises daylight factor. As these two objectives can have conflicting solutions, results showed a series of optimal designs, as seen in Figure 2.18.

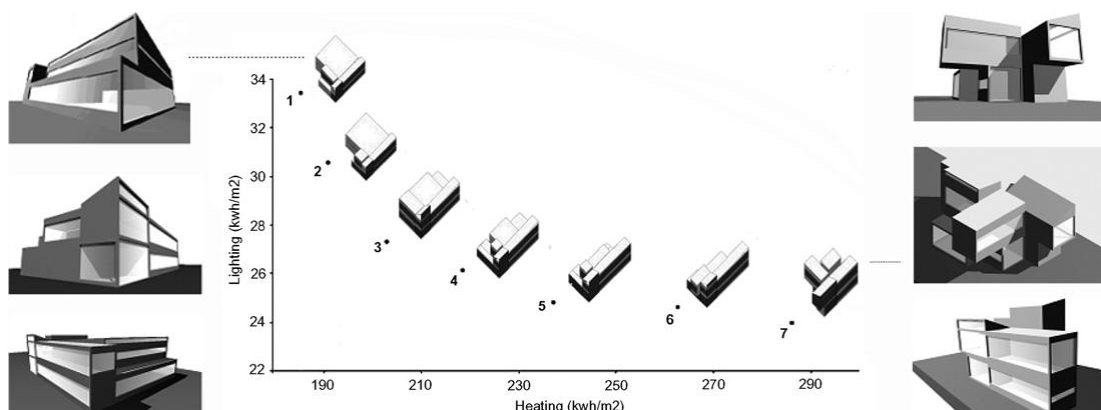


Figure 2.18: Multi-objective 'bottom-up' shape optimisation approach – Energy consumption and Lighting loads (Caldas, 2008)

While the abovementioned studies have examined the relationships between buildings shape and their environmental performance, the examined geometric modifications were quite basic – aspect ratio, windows, overhangs or louvre dimensions. The alteration of spatial arrangements or layout, for the purpose of environmental performance, is still very limited as these are regarded more difficult properties to control and involve relatively complex operations for simple parametric tools. Therefore, the integration of automated generative design programming into thermal simulations and optimisation techniques to evaluate the performance of a range of building layouts and spatial arrangements can address this limitation and consequently provide a powerful decision-making support tool.

2.5.4. Summary

Due to the growth in the use of optimisation methods in the research of the built environment following this review, the following points are noted:

- This review of literature has shown that using optimisation algorithms can significantly decrease the search time for optimal design, compared to brute-force simulations, with Genetic Algorithms presenting the best results.
- Refurbishment optimisation: This review concludes that while the optimisation of refurbishments of existing buildings in term of life cycle performance is possible, it is rarely carried out due to various challenges in its implementation. While a few studies have optimised refurbishment of buildings using single objective methods and limited life cycle scopes, a knowledge gap exists in attempts for coupling multi-objective optimisation, thermal simulations and life cycle performance analysis.
- Generative design: The review has shown that while generative design gains increasing attention in research and practice, the integration of generative design with optimisation is still a major challenge. Only a handful of studies have optimised

buildings perimeter shape (a "top-down" approach) and only a few studies have generated whole building designs to optimise the entire building, including its shape.

- It is noted that while optimisation algorithms can reach very-close-to-optimal solutions, they do not necessarily always reach global optimums. To increase the chances of finding global optimums, the algorithm's stopping criteria has to allow a large-enough number of search samples throughout the search space. This, however, will lead to an increased number of simulations in the case of building performance optimisation, and requires more time and computing power (El Semelawy et al., 2012).

2.6. The Knowledge Gap

The following key-points have emerged from the literature review:

- There is a lack of evidence regarding the LCCF and LCC performance of refurbished and new buildings, and discussion on this research domain is still limited.
- Life Cycle approach is becoming a more common building performance evaluation approach, however, examples for its integration in the research of the built environment are still scarce. This is partly due to the complex mechanism involved in its implementation.
- In the last decade, optimisation has become a more widely-used research technique in the built environment. Current research that uses building optimisation, in terms of environmental and economic impacts, has shown various levels of complexities.
- Some refurbishment-optimisation studies and a few new-built-optimisation studies, in a life cycle perspective, were found. No studies that use optimisation on both refurbished and new buildings were found.
- The computational developments of the recent years, in the form of generative design, environmental performance and thermal simulations, have a great potential in assisting design teams in designing efficient buildings, however, the integration between these three components is still extremely challenging.

Chapter summary:

To Refurbish or to Replace:

- A literature review has shown that studies that examined this issue could not draw a clear conclusion.
- Most of the existing literature does not rely on actual case studies: Evidence to support the advantage of one approach over the other - lacks.

Life Cycle Studies in the Built Environment

- Analysis of resource flows (energy/CO₂/costs) in buildings are divided into five components: Embodied, operational (use), end-of-life, recycling and renewables. ISO 14040, 2006 - Life Cycle Assessment (LCA) framework – sets the basics for analysis of the life cycle environmental impacts of products and services.
- EN 15978:2011 – Sustainability of construction works – is the adaptation of ISO 14040 into the built environment, in the form of Life Cycle Carbon Footprint.
- BS ISO 15686-5 - Building and constructed assets - Life-cycle-costing – is a British standard that details the principles of life cycle costing for buildings and construction assets.

Life Cycle Carbon Footprint (LCCF) of New and Refurbished Buildings

- A systematic literature review, examining the LCCF of 263 case study buildings (48 academic papers) aimed to:
 - Create, for the first time, a benchmark of the LCCF in buildings
 - Examine various factors that might contribute to the LCCF of refurbished and new buildings.

- Compare the LCCF of new and refurbished case study buildings.
- The review has found that:
 - More than 90% of the examined buildings emitted less than 8,000 kgCO₂/m² throughout their lives.
 - Embodied CO₂ emissions account for between 3-77% of the overall LCCF (mean = 24). Operational-related-CO₂ emissions account for 23-97% of total LCCF (75% average) and End of Life CO₂ emissions account for between 0.1% and 2.9% of the total building LCCF (Average = 1.0%).
 - A weak relationship was found between Life Cycle Energy use and Life Cycle Carbon Footprint.

A weak relationship was found between LCCF (kgCO₂/m²/60 years) and the overall floor area of case studies or number of stories.

- Buildings that used district heating technology to deliver space heating usually resulted in an overall low LCCF.
- The study matched LCCF results with climate types.
- While refurbished buildings tend to perform better than new ones (in terms of LCCF), some new buildings still performed better than the best refurbishments. It is, therefore, yet hard to determine which alternative can be considered as better.

Computational Analysis Techniques

- Optimisation methods - The section introduces some background concepts (mathematical optimisation, brute force, local and global optimums and others)

- Generative Spatial Design Programming – two strategies for generating building design, using parametric programming, have been identified and classified:
 - a ‘top down’ approach, in which a fixed given space is divided into smaller ones, or a contour of a building is manipulation by applying a set of simple rules.
 - A ‘bottom up’ approach, in which individual spaces within the building are manipulated separately, to create a new building form.

The Application of Computational Techniques in the Built Environment

- Optimisation algorithms that are commonly used in the research in the built environment were introduced.
- The fields in which optimisation algorithms are used in the built environment were identified and discussed (structural systems and environmental performance optimisation)
- The integration of generative design with optimisation algorithms was presented, and the potential use of this technique to generate and optimise whole buildings was discussed.

3. Methodology

This chapter discusses the research main fields of interrogation and covers the proposed study flow – the processes of the development, validation and implementation of the research proposed computational framework. The proposed framework is then presented, and the development of its different components is detailed. This is followed by an introduction of the methods and tools used for the implementation of the framework and a step-by-step description of the implementation process. Finally, the chapter ends with a description of the validation and verification of the framework.

Traditionally, research is carried out through the observation and investigation of phenomenon in a 'natural' environment. These observations can provide evidence for patterns in the behaviour and operation of the observed system, and for the development of theories around it (Wainwright & Mark, 2005).

In the built environment domain, quantitative research approach – a research tactic that aims at finding relationships between cause-and-effects of a phenomenon – is often used.

The implementation of research often requires the integration and utilization of various research techniques. In this case, to answer the research question, the integration between existing and specially-designed tools (tools that had to be developed or tailored especially for this research) had to be achieved.

The design of this research is therefore focused on the development, testing and validation of a proposed computational framework, which is then implemented using a series of case study buildings.

The design of this research can be broken down to the following stages, as illustrated in Figure 3.1:

A. Development (Chapter 3)– The development of a computational framework: At this stage, the case study interrogation approach is developed and the different stages of carrying out a case study analysis are identified. Furthermore, the various tools that

are utilised in a case study analysis are selected, and the integration between these tools is set out.

- B. Validation (Chapter 4)** – At this stage, key steps in the proposed computational framework are tested through a series of pilot studies, to validate the proposed methodological process.
- C. Implementation (Chapter 5)** – Once the proposed computational framework is developed, tested and validated, it is implemented on the selected case study buildings, to find the favourable design alternative – the refurbishment of existing buildings or their refurbishment, in terms of LCCF and LCC.

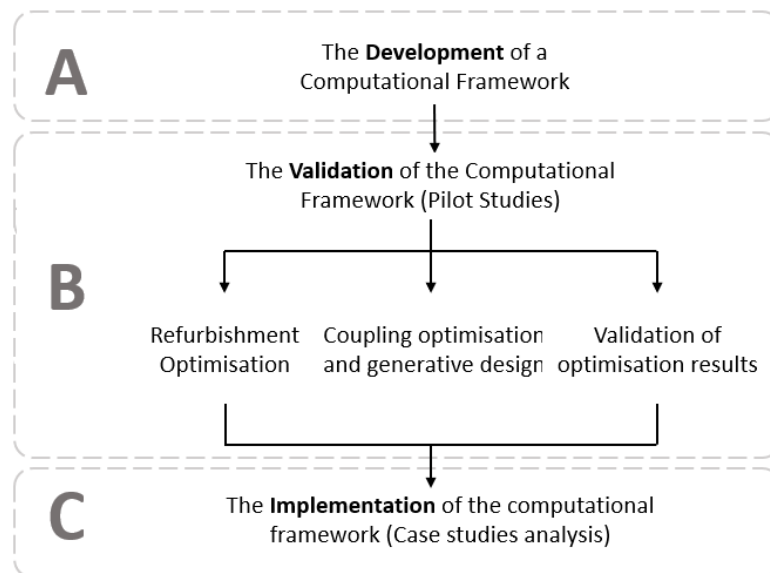


Figure 3.1: Research flow – the development, validation and implementation of the computational framework

3.1. Research Design – the Development of a Computational Framework

To answer the research question, as stated in section 1.2, this research proposes to carry out an iterative comparative case study analysis between the LCCF and LCC of modelled refurbished buildings and those of their replacements. To facilitate this, a computational framework is developed, to automate the calculation of the LCCF and LCC of multiple designs and for identifying the favourable alternative.

The development of the computational framework and the methodology of this research (Stage A) are illustrated in Figure 3.2. The analysis of each case study is comprised of six steps. These steps were grouped into three framework components.

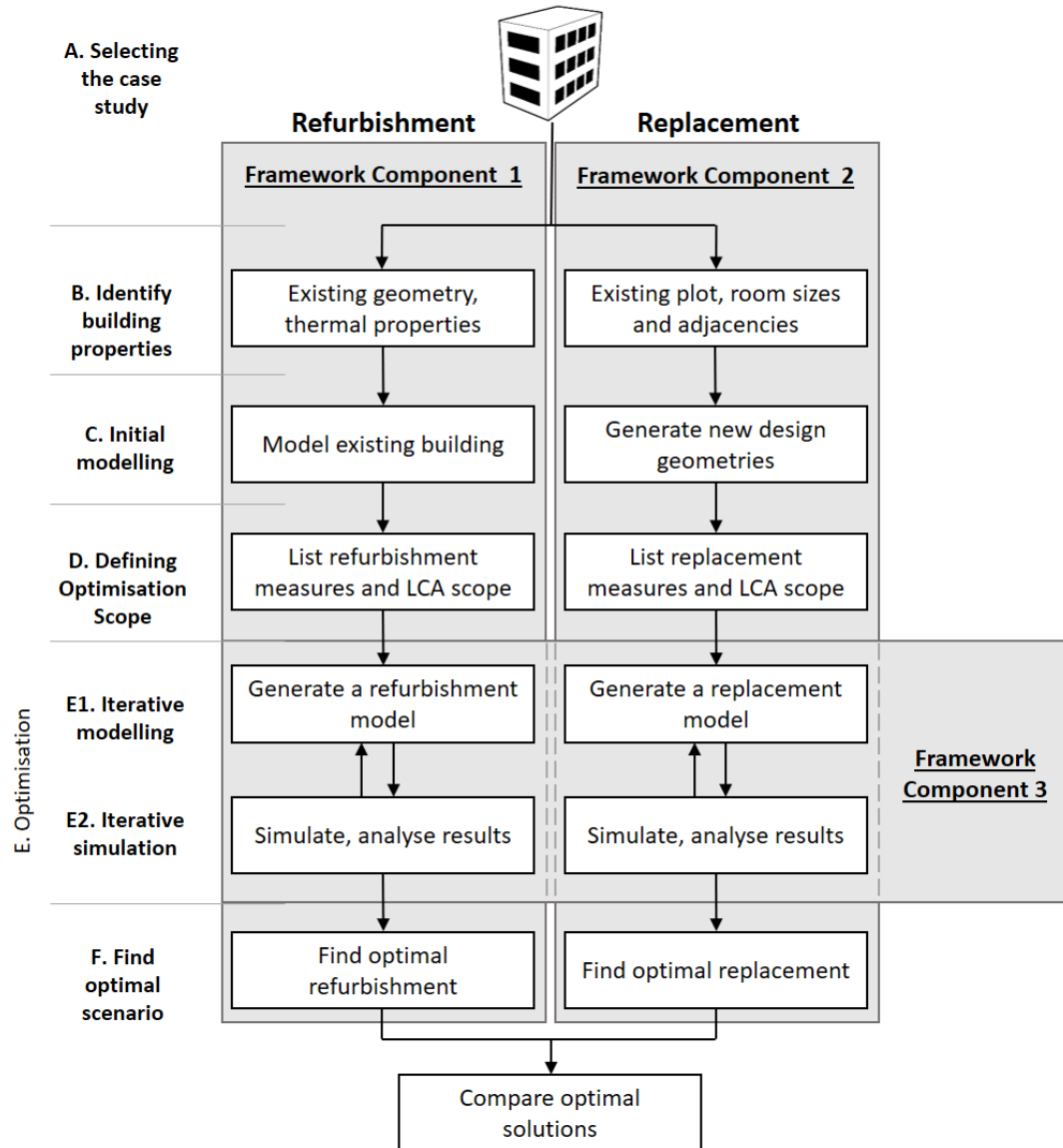


Figure 3.2: Research design – The proposed computational framework

3.1.1. Framework Component 1 - Optimising the Refurbishment of a Case Study Building

The first framework component tests the potential use of optimisation methods for finding optimal refurbishment measures for existing buildings, in respect of their LCCF and LCC. More specifically, this sub-framework aimed to understand how computational optimisation methods (Genetic Algorithms) could be utilised to identify the optimal combination of refurbishment measures that will minimise LCCF and LCC. Furthermore, the study tested the applicability of this design approach and its potential impact on LCCF and LCC, to support decision-making, compared to more commonly-used approaches.

3.1.2. Framework Component 2 – The Generation of Optimal New Designs using PLOOTO - Parametric Lay-Out Organisation generaTOr

The aim of the second framework component was establishing a mechanism with which the design of new buildings could be automatically generated, and their design properties could be optimised using an ‘of-the-shelf’ optimisation toolkit.

For this, the second framework component required the development and testing of an automated generative spatial design application, that could come up with feasible new designs alternatives (based on a set of design requirements), and its coupling with thermal simulations and with an optimisation application.

In particular, in developing this sub-framework it was essential to explore:

- a. How can a generative spatial design application be developed?
- b. How can the output of the generative spatial design application be fed as an input to a thermal simulation application?
- c. How can the output of the thermal simulations inform an optimisation algorithm?
- d. How can this optimisation algorithm amend design properties, to improve overall life cycle performance?

3.1.3. Framework Component 3 – The Validation of a Life Cycle Performance GA Optimisation Application

This research aims to evaluate and improve the performance of buildings in terms of their life cycle performance – a metric that requires the evaluation of impacts incurred by multiple processes. This requires, in technical terms, a unique set-up for the optimisation procedure to enable a life-cycle evaluation of building performance.

Since the currently available optimisation tools cannot facilitate such an objective function, in the last framework component a designated optimisation algorithm was developed and tested, and its results were validated to ensure its performance and results are robust. In particular, the optimisation application was tested for its capabilities to:

- a. Access .idf files, 'read' surface areas and sum relevant embodied CO₂ and costs.
- b. Send .idf file for thermal simulation and retrieve their operational performance.
- c. Control the breed, cross over and mutation of models.
- d. Modify .idf files to improve model performance.

3.2. Methods and Tools

To carry out the research and achieve the research aims and objectives, a combination of methods and tools are used in the study design. At the core of the methodology is a combination between the principles of comparative case study analysis and modelling & simulation, where multiple design scenarios are modelled, simulated, their outputs are compared and the favourable scenario is identified.

3.2.1. Comparative Case Study Analysis

Case study analysis is a research approach that aims to understand the dynamics of a phenomenon within a specific setting (Eisenhardt, 1989; Amaratunga & Baldry, 2001), or as Yin (2014) states – it is "an empirical inquiry that investigates a contemporary

phenomenon in depth and within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident". Case study analysis is widely used in the research of the built environment and in the field of buildings thermal performance (Amaratunga et al., 2002).

The case study technique has been chosen for this research due to the nature of the research: LCCF and LCC are site-specific metrics. Both are closely tied to local factors, such as climate, energy production process and local building material supply chains. The case study approach suits these limitations as it focuses on individual building settings - it emphasizes the intensive analysis of a single setting of a phenomenon (Amaratunga et al., 2002).

a. Principles

Case studies can perform single or multiple-case investigations (Yin, 2014). Multiple case study analysis is analogous to multiple experiments: the repetitions attempt to validate results and to evaluate how robust they are (Darke et al., 1998). Furthermore, case study replication is used for comparing individual cases and for finding similarities in their behaviour (Yin, 2014): The development of new theories can be done by drawing evidence across multiple cases and by an iterative process of investigation, in which individual properties of the case studies are isolated (Amaratunga & Baldry, 2001; Amaratunga et al., 2002).

b. Limitations

Some researchers assert that the case study approach is not robust enough and that it might be prone to be biased, as subjective judgment, generalization and a-priori theorisation might influence study results (Darke et al., 1998). Other scholars point out that building theories from case studies may be too narrow and generalized, as the effort in characterising case studies does not always allow an investigation of a large sample of cases, from which a theory can be developed. This increases the risks of reaching only a

partial understanding of the examined system patterns partially (Eisenhardt, 1989; Amaratunga et al., 2002).

3.2.2. Modelling and Simulation

Modelling and Simulation (M&S) are two individual and equally important research concepts (Padilla et al., 2011). M&S are used for exploring the behaviour of a system or a phenomenon, and for generating hypothesis that explains relationships between different components in an examined system (Wainwright & Mark, 2005). Models are defined as the abstractions of reality – they represent a complex reality in the simplest possible way (March & Lave, 1975; Wainwright & Mark, 2005). Simulation is the execution of a model, and the evaluation of its behaviour over time (Tolk, 2010). While other research methods are often limited to the examination of historic events, simulations enable the examination of future ones (Dooley, 2002).

a. Principles

Computer M&S have become more widely used due to recent advances in computer science (Tolk, 2010). M&S involve a computational representation of a systems and the processes these system experience in the real world (Davis et al., 2007), and in a sense, aim to mimic real world conditions to conduct experiments in a virtual setting.

To enables a simulation of a system, it is essential to know and understand its inner structure: The external behaviour of a system (the output of a simulation) is the result of the relationship between its inputs and its operation mechanism (Zeigler & Kim, 2000). Davis et al. (2007) described a roadmap for the implementation of M&S procedure. In the roadmap, running the simulation is described as the equivalent of conducting experiments, and result verification is equivalent to evaluation of the experiment results.

The M&S technique is used in this resesarch it allows a simple representation of the complex systems, such as those of the built environment. Moreover, M&S is ideal as it

allows a flexibility – quick adaptations and iterations of the experiment settings can be easily implemented, as well as the conduction of rapid repetitive experiments (Zott, 2003; Tolk, 2010). Furthermore, M&S is a quantitative research method that provides objective rather than subjective outputs, and makes the formulation of a model possible (Enger, 1970; Amaratunga et al., 2002; Panas & Pantouvakis, 2010).

b. Limitations

While M&S can be conducted faster than real time experiments, and while this approach offers a 'sterile' experimental environment (Padilla et al., 2011), researchers must be mindful with modelling assumptions, conceptualizations and with the way models are implemented (Tolk, 2010). Simulation errors might occur due to poor resemblance between the reality and how it is interpreted in the mind of the modeler, or due to representational capabilities of modelling tools (Matthews, 2012; Page et al., 1994; Dooley, 2002). Computer limitations are also a risk - the use of particular computer languages or software might have a direct influence in the structure and results of the model (Nance, 1983).

3.3. Implementation

The implementation of this research followed the research design stages, as illustrated in Figure 3.2, and involved the integration of a number of applications and tools which were selected after a careful evaluation of available applications. As some required functionalities could not be delivered by existing tools – some computer applications had to be developed especially for this research.

A. The Selection of the Existing Case Study

In the first step, the case study to be analysed is selected. In this first step, major issues within the building, if any exist (adjacencies, design limitations or any other unique circumstances) should be identified to ensure the building can undergo the analysis.

In this research, all examined case study buildings, both for refurbishment and for replacement, are residential. All buildings typical prototypes of residential buildings in London (having the same climatic conditions), as identified by Oikonomou et al. (2012). Specifically, these included a two-story mid-terrace house, a single-story bungalow and a block of flats.

Embodied CO₂ figures were taken from products EPDs whenever available for the majority of cases. The Bath Inventory of Carbon and Energy (Hammond & Jones, 2011) was used when material data were missing. Material costs were taken from manufacturing pricing sheets and from Spon's Architects' and Builders' Price Book (Langdon.D, 2013). Operational emission rates and energy costs estimations were based on the NCM (2013) and UK Power (2017), and room usage profiles and internal loads were based on the NCM (2008).

B. Identifying Building Properties

Next, building properties that contribute to the case studies performance are identified. *Refurbishment:* These included an investigation of the geometries of the original buildings and the relationships between spaces within them, as well as included the identification of the existing buildings' thermal properties, such as surface build-ups, materials use and window sizes.

Replacement: For the replacement alternative, the existing plot size had to be clearly defined, and an extended list of thermal zones, room dimensions and adjacencies of a possible replacement was set out, in addition to a list of potential build-ups. Assumptions regarding build-ups and building materials can be found in Tables 5.2, 5.3 and Appendices A and B).

C. Initial Modelling

Next, computational representations of the buildings in the different scenarios are formed for the purpose of carrying out thermal simulation analysis.

Refurbishment: The original existing building is modelled, based on the characteristics that had been identified in the previous stage. This was done using the Sketchup Legacy OpenStudio plug-in and later manipulated in the IDF Editor interface, if required.

Replacement: The initial modelling of the replacement scenarios, geometric representations of new building designs, in the form of an .idf file, were generated. This was done by using Python to develop a designated computer application – ‘PLOOTO’ (Parametric Lay-Out Organisation generaTOr), based on principles from studies which were outlined in the literature review (section 2.4.2). PLOOTO uses a heuristic approach to generate spatial arrangements which has the following operation mechanism:

- To allow a true non-biased search, points are randomly distributed across the given plot. Each point represents a room, and will, at the end of the spatial arrangement process, be surrounded by four walls, a ceiling and a floor.
- Various rules and conditions are applied for each point, e.g.: ensuring the width and length of each room are within a pre-defined dimension range, making sure a room proximity matrix is followed, confirming that no room exceeds the plot boundaries etc.
- External and internal walls are detected.
- Windows are added to external walls, following a user-defined predefined window-schedule input.
- Usage schedules (internal loads, thermostats set-points, occupancy times etc.) are automatically applied to the different rooms.

Instead of setting the initial point to the centre of a room, PLOOTO is designed to allow flexible wall placing: The room boundaries can move towards the initial point and away from it, if necessary, to increase the chances of finding a spatial arrangement where all rules are followed (as seen in Figure 3.3). This process is then repeated floor-by-floor, while ensuring that vertical cores within the building are stacked one on top of the other.

Replacement: The alternative replacement designs, as generated by PLOOTO, are introduced. The embodied CO_{2e} of the original building is calculated, as well as that of the components that are to be removed as part of the refurbishment, to be accounted for when calculating the replacements LCCF. For the replacement scenario it is assumed that the case study buildings are demolished completely, and that all of their components are buried in landfills.

For a detailed description of the research scope and the processes that had been taken into account in the LCCF and LCC calculation, please refer to section 5.1.3.

E. Optimisation

As illustrated in the research design (Figure 3.2), the NSGA-II optimisation procedure is composed by two sub-process. These are further illustrated in Figure 3.4:

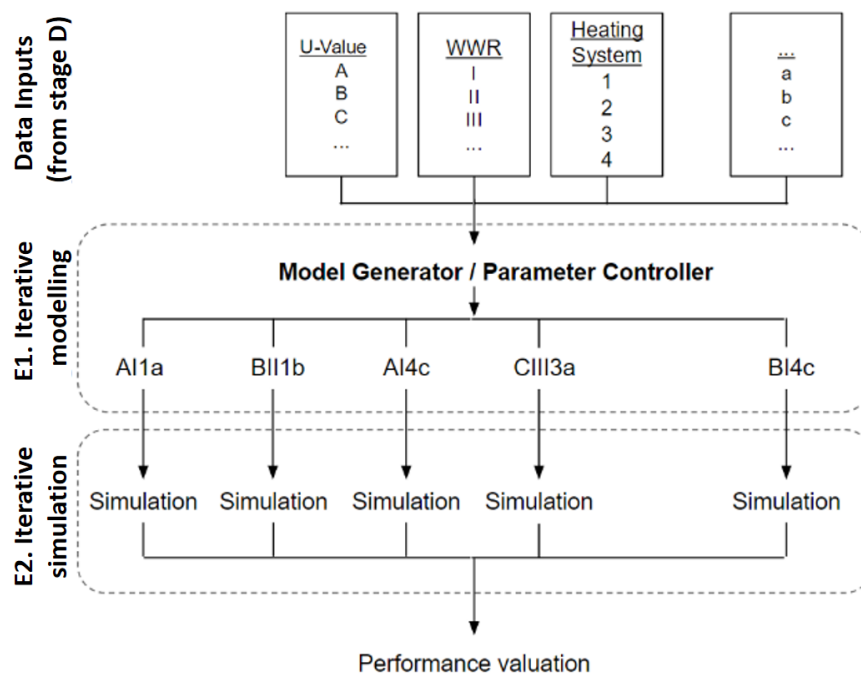


Figure 3.4: The steps of a parametric thermal simulation adapted from Zhang, 2012)
Each element in stage E1 is composed by genes from stage D (data inputs). For example, the first element in E1(AI1A) has the 'A' phenotype from U-Value, the 'I' phenotype from WWR, the '1' phenotype from heating system etc.

E1. Iterative Modelling

In the iterative modelling stage, thermal models are generated through the selection of building thermal properties, based on the possible pre-defined data input parameters. The process of generating and amending thermal models is carried out using a parameter controller - a computed application that enables the automatic modification and update of a large number of models. (Naboni et al., 2013). Unlike most available parametric controllers, the controller that had been developed as part of the designated NSGA-II application for this research enables not only the modification of basic building properties (build-ups or simple geometric modifications) but also the selection of different building layouts.

By the end of this process, a complete thermal model is constructed and sent for simulation.

E2. Iterative Simulation

Once models are generated – they undergo a thermal simulation, using the usage profiles, weather file and thermal properties as defined at the modelling stage. The annual energy consumption of each model is then calculated using EnergyPlus, and the associated CO_{2e} and costs are calculated.

To calculate embodied CO_{2e} and costs values, the NSGA-II application accesses each model, reads the relevant surface areas and their associated build-ups automatically. Once the embodied and operational values are obtained - the overall LCCF and LCC calculations are carried out.

Once LCCF and LCC are calculated, the NSGA-II algorithm analyses the simulation results and carries out a set of manipulations on the building properties, to be implemented in the next generations of models.

F. Finding an Optimal Scenario

Once the LCCF and LCC of the optimal design (or designs) in both the refurbishment and replacement scenarios are found, tailored post processing applications are executed to automatically generate a set of analysis outputs that enable an investigation of the pareto-optimal models. Finally, the system's overall favourable solution is identified and a set of recommendations are laid out.

3.4. Testing, Validation and Verification

The validation and verification of models is an essential part of case study analysis and modelling and simulations (Tolk, 2010). Computational models are especially prone for faults, as a computer bug or unnoticed human error might generate faulty results (Sargent, 1998).

Based on Davis et al. (2007) and Darke et al. (1998), the following issues were considered during the design and implementation of this research, to improve the confidence in the research results and to minimise the level of uncertainties:

3.4.1. Study Design Validation

The way experiments are conducted is highly important, as findings and conclusions are the results of the process of carrying empirical experiments. Studies that are based on the wrong set of assumptions, or studies in which a limited scope is examined, for example, might end with a biased set of results. In this research, all case studies and assumptions were based on well-established literature protocols and standards.

Furthermore, to increase the confidence in the robustness of the study design, each stage of the proposed computational framework was tested independently using a pilot study (three studies in total). The aim of which are discussed in section 4.

3.4.2. Data Input Validation

The accuracy of collected data is important for simulation validation and verification of results, especially when performing computational simulations where validation of input variables is harder. Data input, during this research, was made with great attention for details and was checked and examined to ensure no faults occurred.

Following the discussion in section 2.2.6, the LCA methodology has inherited uncertainties in limitations. The following strategies were taken to minimise the risks of uncertainties:

Embodied CO₂ and Cost calculations - In the calculation of materials embodied CO₂, only building materials and components that had Environmental Product Declarations (EPDs) were used, whenever possible. As discussed in 2.2.4, EPDs are standardised certificates that follow the EN 15804:2011 protocol – an assessment framework for building material sustainability.

As a small number of building materials did not have EPDs, the well-established Bath ICE (Hammond and Jones, 2011) – a database that aggregates the embodied CO₂ of various building materials across the UK – was used. This method is widely used across the built environment LCA discipline (as discussed in Table 2.6 of the literature review– “Embodied CO_{2e} calculation method”).

To ensure that the automatic aggregation of the embodied CO₂ and costs of the modelled case study buildings was accurate, the output values were tested and compared against hand-calculation of the same models.

Operational CO₂ and Energy Cost calculations - For the calculations of operational-related CO₂ emissions and costs, the energy consumption of the examined buildings was calculated using EnergyPlus – one of the most commonly used thermal simulation tool. Operational CO₂ rates and energy costs were calculated using (NCM, 2016; UK Power, 2017)

It is acknowledged that outputs from thermal simulation can vary, depending on various factors, such as calculation algorithms and methods, user skills and experience, modelling technique and others (Raslan & Davies, 2009; John, 2010; Sun et al., 2014). To minimise the potential impact of those, all models were constructed automatically – using a computational application – and all simulations were carried out using the same thermal simulation tool.

3.4.3. Optimisation Validation and Verification

To ensure that the optimisation algorithm has reached the actual optimal solutions, two main tactics were used:

- A. The NSGA-II optimisation algorithm was tested by examining a simple case study building. The optimisation outputs – a set of pareto-optimal models – were then compared against the simulation of the entire search space of that particular design scenario. This study is presented and further discussed in section 4.3.
- B. For each case study building in the “Implementation” chapter (Chapter 5), three separated optimisation runs were carried out, to increase the confidence in finding the global optimum, and to make sure that the pareto-optimal models did not depict local optimums.

3.4.4. Generative Design

This study used a designated tool – PLOOTO – for the generation of non-biased building layouts and spatial arrangements. Two main tests were performed on PLOOTO, as further discussed in section 4.2:

- A. PLOOTO’s capability to explore and find a maximal number of design solutions, given a set of restrictions, were tested.

- B. PLOOTO's outputs were regularly checked to ensure that the structure of the .idf file is sensible, and that all building materials and usage profile are defined in the proper way.

It is noted that in generating new spatial arrangements, PLOOTO was stopped once it reached a certain number of different designs, as new designs showed great similarities to previous ones. It is, therefore, acknowledged that PLOOTO may have been stopped before it had reached all possible design solutions.

Chapter summary:

- The research flow and its three main components – the development, testing & validation of the computational framework – are presented.
- The methods and tools used in this research were introduced.
- The research design was introduced and the concept behind the proposed computational framework was discussed.
- The sub-processes of each step of the proposed framework are presented in detail. This included the development.
- The implementation of the research was described. This included an introduction to the concept of a comparative case study analysis, and the two main methods used in this research: case study analysis and modelling and simulation.
- The validation and verification processes are discussed. This included ensuring the data input are based on reliable sources, testing the optimisation framework and evaluating the generative design procedure.

4. The Development, Testing and Validation of the Proposed Computational Framework

This aim of this chapter is to establish, test and validate the different components of the proposed computational framework and the tools used in this research. This is achieved by using three pilot studies to examine the following framework components: A) Exploring the proposed approach for optimising a refurbishment of an existing building. B) Examining the proposed approach for optimising a replacement building and the PLOOTO application. C) Validating the capabilities of the designated parametric controller and the NSGA-II optimisation application. The aim of each pilot study is described, its scope and methodology are set, and results and execution are finally presented. Each sub-chapter ends with a short discussion and conclusion about the robustness of the examined approach.

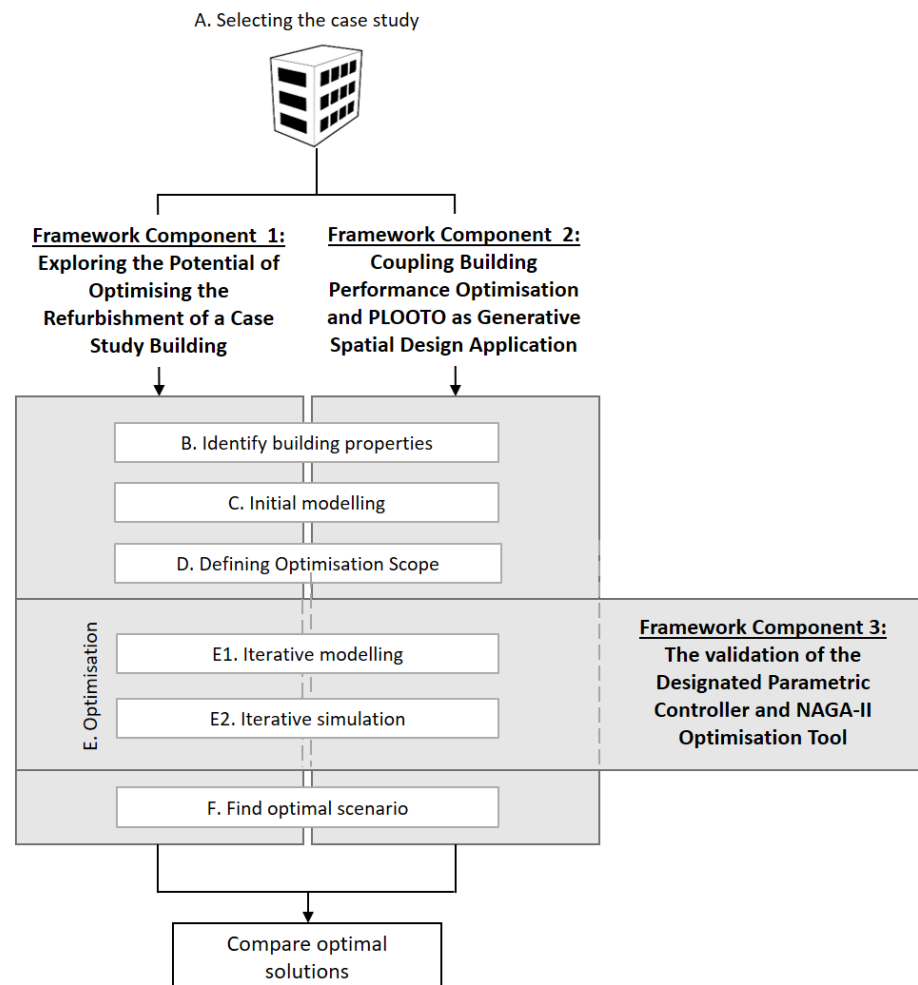


Figure 4.1: The research design and the components examined by the pilot studies

4.1. Framework Component 1: Exploring the Potential of Optimising the Refurbishment of a Case Study Building

4.1.1. Aim

The aim of the first test was to examine the potential of using optimisation techniques in finding optimal designs for a refurbishment scenario. This was implemented using a pilot study¹, by examining the use of NSGA-II to minimise the case study building's LCCF and LCC. In particular, the study's main research question was:

- How can a computational optimisation method be utilised to identify the optimal envelope refurbishment measures to minimise LCCF and LCC of a case study?

To achieve this aim, the following objectives were set:

- Using the proposed method, what are the optimal refurbishment design's LCCF and LCC, and what is the balance between the embodied and operational CO₂ emissions throughout the optimal refurbishment's life cycle?
- How can the proposed method be used to examine life-cycle performance in buildings?
- How does the life cycle performance of the optimal design compare with that of the original building, and the actual refurbishment?
- What is the impact of using LCCF and LCC to support the design decision-making process as compared to other more commonly used performance-based methods?

4.1.2. The Case Study Building

The examined case study building is a recently refurbished "Grade II listed building" council housing complex. The complex was initially built in the late 1950s in Sheffield, England, and after a slow deterioration, during the 1980s, a scheme for its refurbishment

This study was published in Schwartz et al. (2016) ¹

was launched in the early 2000s. The study focuses on a specific section of the complex - a north building (A) and a south building (B) which are two similar blocks with different orientations (Figure 4.1). As different orientations can lead to differences in energy consumption, the study set out to examine the performance of the refurbishment of both buildings separately.

The original building envelope was considered to have poor thermal performance. Moreover, as exposed concrete frames were one of the main architectural features in the original design, it was a high priority for the refurbishment to retain them. While this approach maintained the original appearance of the building, it could lead to an increased risk of thermal bridges, which might be associated with high energy consumption and the formation of mold on interior surfaces.

While the building estate uses a district heating system, to provide space and domestic hot water, the analysis examined the impact of using different sources of heating supply systems on the buildings life cycle performance by examining two different systems: A) district heating. B) the more commonly-used gas boiler supplied space and water heating.



Figure 4.2: Park Hill site plan



*Figure 4.3: Park Hill after construction.
Source: <http://www.28dayslater.co.uk/forums/showthread.php/74904-Park-Hill-Flats-Sheffield-October-2012>*

4.1.3. Methodology and Study Design

To examine the proposed approach and to undertake the parametric optimisation, the following tools were used (as shown in Figure 4.4):

- EnergyPlus was used for carrying the thermal simulations.
- jEPlus – a simple parametric controller interface for EnergyPlus users, that enables the amendment of parametric simulations within the EnergyPlus simulation environment.
- jEPlus+EA – an NSGA-II interface that allows the integration of genetic algorithms optimisation with simulations under EnergyPlus.

Figure 4.5 illustrates the sequence of the study execution and the tools that were used to carry the study. Emission rates and energy costs estimations were based on the NCM (2013) and National Statistics (2018).

The initial geometry was modelled in Sketchup and then exported to EnergyPlus Input Data File using the Legacy Open Studio plug-in for Sketchup. The model's thermal properties (weather file data, HVAC system, occupancy rates etc.) were identified in EnergyPlus. The optimisation objectives (LCCF and LCC), mutation, number of generations and crossover rates were all set in jEPlus+EA.

As the study examined the impact of using two different heating supply systems (district heating and gas boiler), these scenarios were tested separately, i.e., the optimisation was ran twice, where the only difference between the two optimisation runs was the heating supply source.

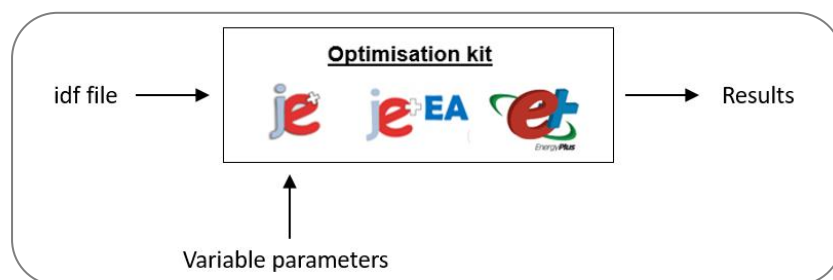


Figure 4.4: Testing framework 1 – study design

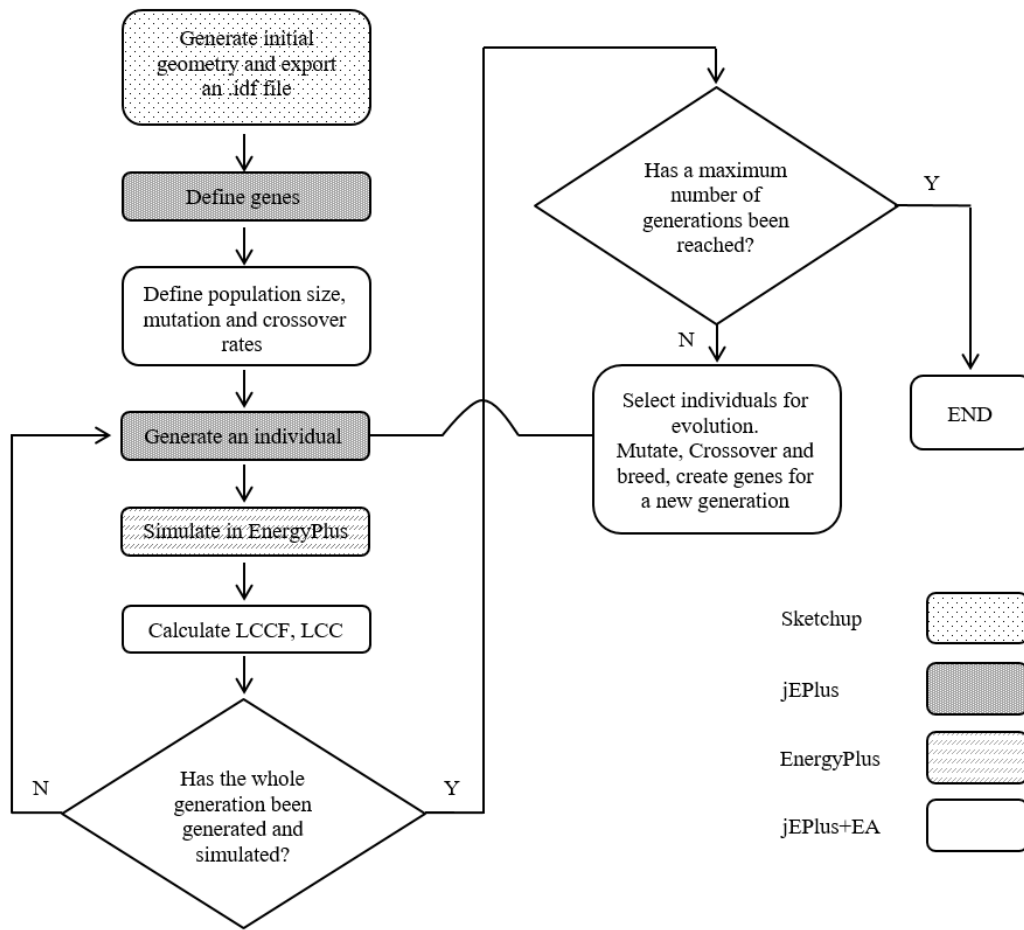


Figure 4.5: Pilot study execution sequence (Based on Tuhus-Dubrow & Krarti, 2010)

4.1.4. Study Assumptions

Material embodied CO₂ and costs were taken from Bath ICE (Hammond & Jones, 2011) and Spon's architects and builders price book (Langdon, 2013).

This study focused on the refurbishment of the building's envelope – the building components which the GA could manipulate are highlighted in Figure 4.6. Table 4.1 shows the building properties for optimisation and their possible values. Overall, a total of 55,296 possible models could potentially be created.

Table 4.1 shows all the building properties that were used in the optimisation, and their alternative values. The life cycle stages, for both the LCCF and LCC analysis, and source of data for that stage, are described in Tables 4.2 and 4.3.

Each optimisation run had a population size of 9 individuals and was run for 125 generations with a mutation rate of 0.2 and a cross-over rate of 1.0. Each project took around 6 hours to simulate, on an i7 Intel processor with 6.0 GB installed memory.

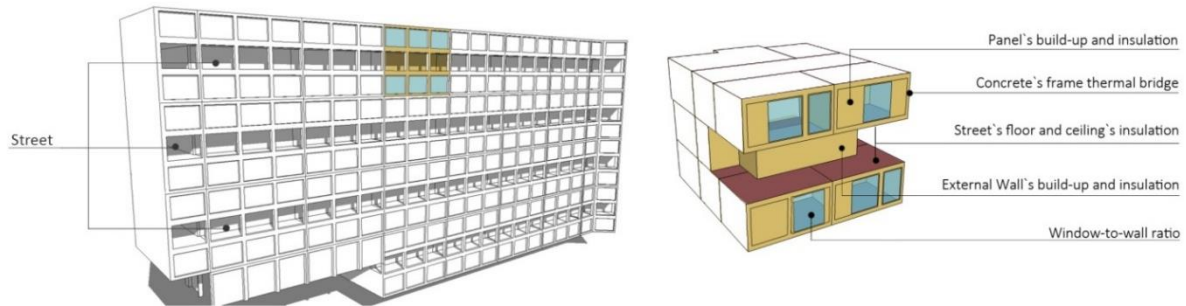


Figure 4.6: Building "B" (left) and the elements for the GA optimisation (right)

Gene number	Name	Possible values
1	Panel Insulation, Street insulation	50, 100, 150 [mm]
2	Exterior Insulation	50, 100, 150 [mm]
3	Bricks	0, 100 [mm]
4	Thermal bridges Insulation	0,50,100[mm]
5	WWR (Top floor, West)	25, 50, 75, 100 [%]
6	WWR (Mid floor, West)	25, 50, 75, 100 [%]
7	WWR (Bottom floor, West)	25, 50, 75, 100 [%]
8	WWR (Top floor, East)	25, 50, 75, 100 [%]
9	WWR (Bottom floor, East)	25, 50, 75, 100 [%]
Total Number of combinations		55,296

Table 4.1: Building properties for optimisation and their possible values

Boundary factors	Data Source
Building Materials Including waste	Sketchup model, Architectural drawings and Bath ICE
Transport	3%*
Construction (labour)	7%*
Energy in use	Energy Plus
Demolition	2%*
Maintenance	See Table 4.3

* Percentages refer to the total building EC- regarded as 100% of "Building Materials including Waste".

Table 4.2: Life cycle stages. Data based on (Cole & Kernan, 1996; Blengini & Di Carlo, 2010; Dixit et al., 2010; Gustavsson, Joelsson & Sathre, 2010; Monahan & Powell, 2011).

	A1-A3			A4-A5		B1-B7							C1-C4			
	Product stage			Construction		Use							End of Life			
	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4
	Raw material supply	Transport	Manufacturing	Transport	Construction	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction	Transport	Waste processing	Disposal
LCCF	✓	✓	✓	✓	✓				✓		✓	✓	✓	✓	✓	✓
LCC	✓	✓	✓	✓					✓		✓	✓				

Table 4.3: Pilot study 1 life cycle scope (based on BS EN 15978:2011)

4.1.5. Results and Discussion

a) Optimisation Results - The study results (Figure 4.7) showed that the utilization of NSGA-II as an optimisation tool was successful. During the optimisation process, simulation outputs successfully converged, reducing LCCF and LCC for both the district heating and the gas boiler scenarios. The system took around 70 generations to converge and find the optimal solutions (with 10 models per generation).

Four groups of models are clearly shown on the graphs – models with and without additional brick layer and individuals with and without thermal-bridge insulation. All optimal models had the thickest available insulation, and insulating the thermal bridge brought to a reduction of between 10-20% in the LCCF and LCC. Results also show that while models with a brick layer have lower operational energy consumption, this layer embodies more CO₂ than it saves throughout the buildings life.

Interestingly, all optimal models in the district heating scenario had small south-facing windows. This means that even a fully glazed south-facing façade – i.e., a facade that allows maximum passive solar radiation heat gains (which might potentially lead to a decrease in energy use and the associated emissions) – embodies more CO₂ than it saves.

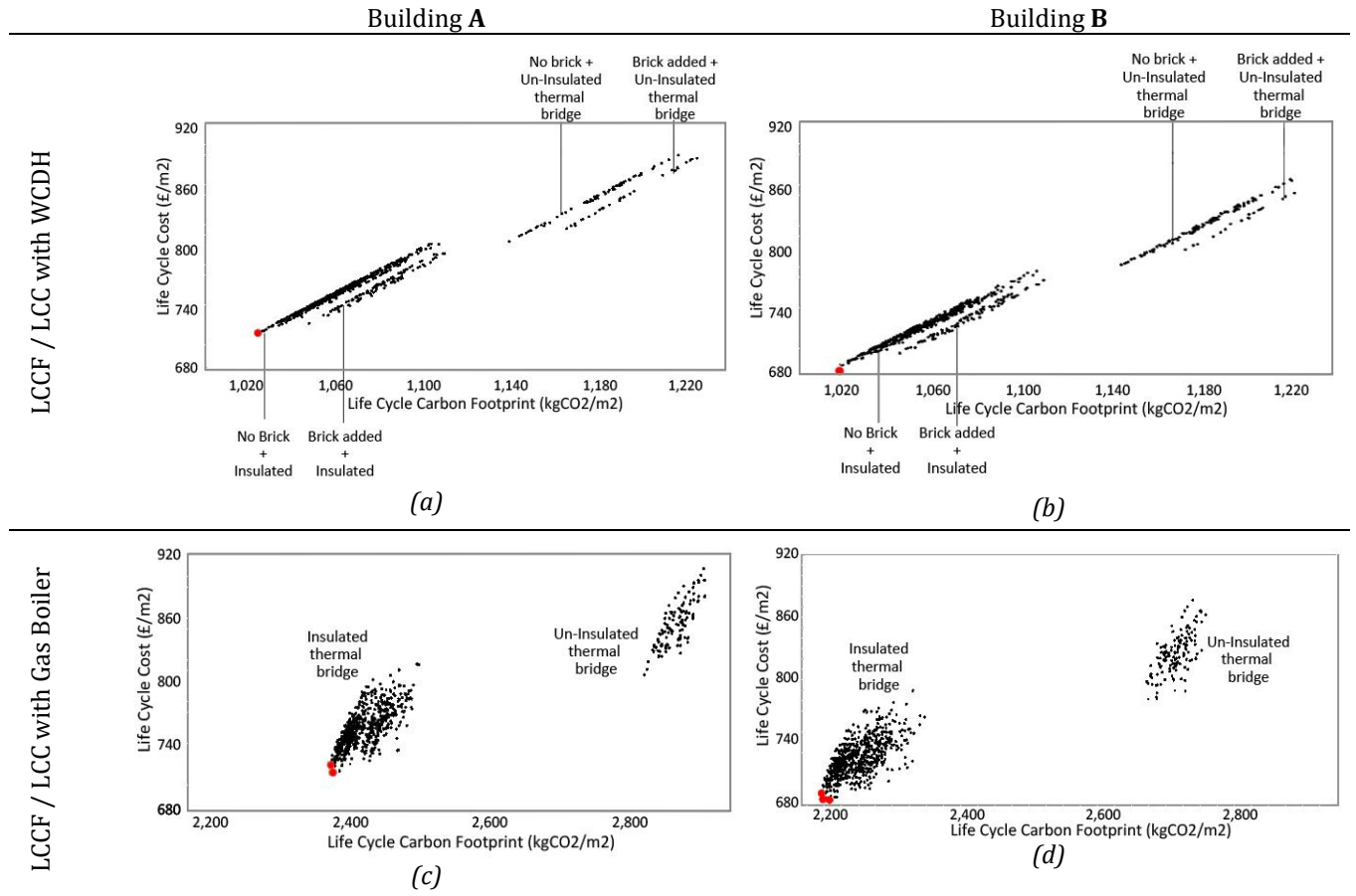


Figure 4.7: Optimisation results – Finding pareto-optimal solutions for the different buildings.

b) Operational-related CO₂ Emissions - The 60-years operational-related CO₂ emissions of the original non-refurbished building were compared to those of the original refurbishment and to that of the optimal design (For this analysis only the district heating supply was considered for space and water heating). Figure 4.8, shows that when comparing operational CO₂ emissions of the 'Non-Refurbished', the 'Original Refurbishment' the mean of all optimal refurbishments, the original refurbishment achieved a 13% reduction in operational emissions throughout its life compared to the non-refurbished building, while the mean optimal refurbishment achieved a reduction of around 29%.

c) Life Cycle Carbon Footprint - In comparing the life cycle performance of the non-refurbished building, the original refurbishment and the optimal refurbishment – Figure 4.9 shows that the original refurbishments emit 20% (or around 200 kgCO₂/m²) more CO₂

than the non-refurbished building. This suggests that the refurbishment managed to improve the living conditions for occupants, while having minimal CO₂ investments. Still, results indicate that the optimal refurbishment could have achieved an even lower LCCF.

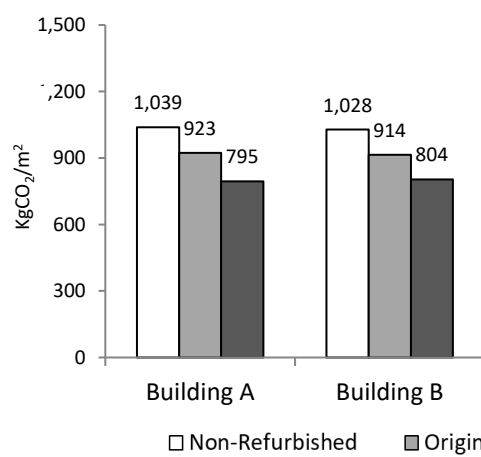


Figure 4.8: Comparison of non-refurbished, refurbished and optimal building options: 60-year operational-energy related CO₂ emissions.

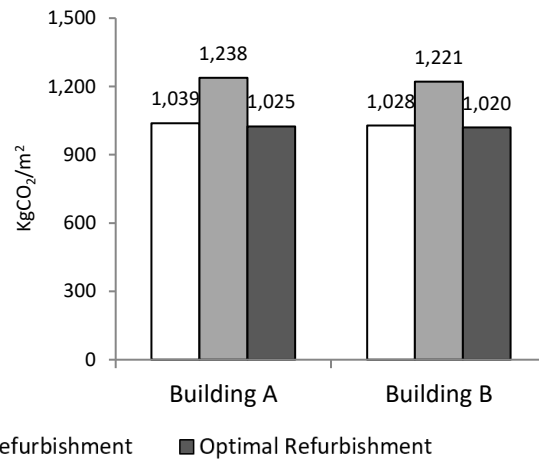


Figure 4.9: Non-refurbished, refurbished and optimal buildings – 60 years LCCF

d) Performance Metric Comparison - As annual energy consumption (kWh/m²/year) is considered to be the primary goal of current legislation (HM Government, 2016) rather than a more comprehensive analysis, such as LCA, a comparison between the optimal designs according to the two objectives was carried out. For this, two fully southern-oriented building optimisation were carried out, using gas boilers for heating: One aimed to minimise LCCF/LCC (kgCO₂/m²/60 years and £/m²/60 years) and the other aimed to minimise annual energy consumption and costs (kWh/m²/y and £/m²/y). As expected, when using operational energy and running costs as the fitness criteria, the model with the largest south-facing windows were selected (as passive solar radiation resulted with reduced operational energy and costs). However, in the LCCF/LCC optimisation, models with the smallest windows were chosen (Figure 4.10). These results indicate that one of the most common tests conducted in the industry – annual energy consumption – might result with buildings having higher life cycle CO₂ emissions values.

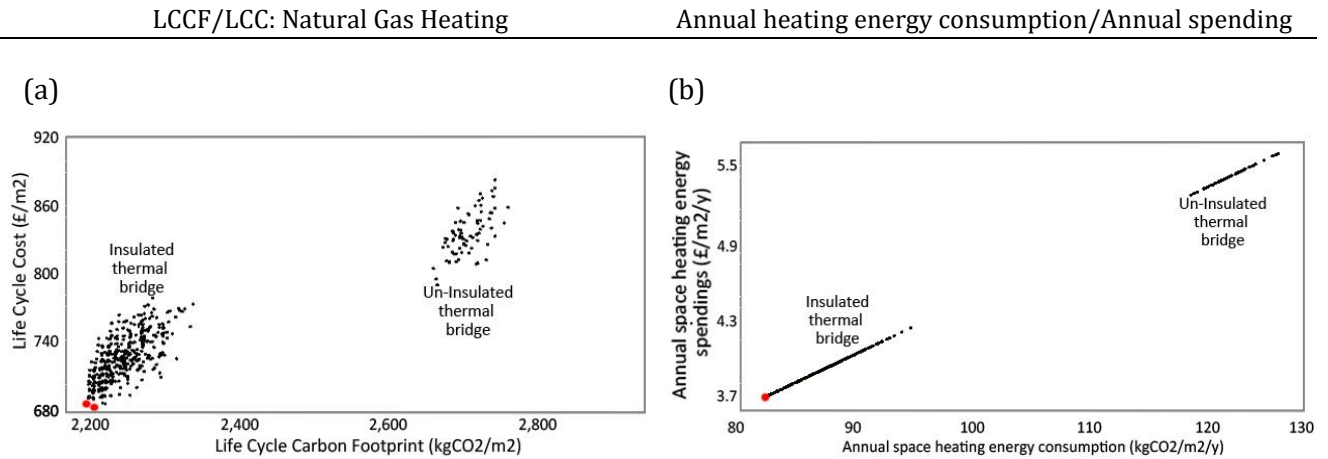


Figure 4.10: Fully south-facing building. (a): LCCF/LCC: Natural Gas Heating. (b): Annual heating energy consumption/Annual spending (Building B)

4.1.6. Findings Summary

Pilot study findings	Implications for the research
1 Computational optimisation was successful in identifying optimal envelope refurbishment measures for the case study, in terms of LCCF and LCC.	Validation of the main study approach – Coupling optimisation algorithms with thermal simulation tools can be utilised to find optimal refurbishments.
2 A range of outputs can be extracted using the proposed methodology, and further analysis can be carried out (e.g., embodied versus operational CO ₂ emissions analysis, comparison between the performance of the refurbished and non-refurbished buildings.	The proposed methodology makes it possible to conduct new analysis and test to the models, and to examine various aspects of life cycle performance
3 Minimal LCCF and LCC figures were found	This contributes to discipline's body of knowledge in terms of LCCF and LCC figures of a refurbishment of a case study building.

Table 4.4: Pilot study 1 findings summary

4.2. Framework Component 2: Coupling Building Performance Optimisation and PLOOTO as Generative Spatial Design Application

4.2.1. Aim

The second pilot study¹ establish a framework that couples parametric thermal simulations and optimisation with automated generative spatial design programming, in order to incorporate different spatial arrangements as a new and independent simulation parameter. In particular, the study is focused on the introduction of PLOOTO (Parametric Lay-Out Organisation generaTOr) as an automatic layout generative design tool, to the optimisation process that was tested in pilot study 4.1.

The focus in this pilot study was purely on the geometrical properties of the building (building shape and window-to-wall-ratio). The study aimed to find the optimal geometry in terms of annual heating and cooling loads. The main research question was, therefore:

- How can PLOOTO – a generative design application – and thermal simulation tools be incorporated within the NSGA-II optimisation procedure, to generate optimal new building designs?

To achieve this aim, the following objectives were set:

- Testing PLOOTO`s capabilities for generating new-designs. This included:
 - Ensuring PLOOTO finds all possible designs for a given design task.
 - Ensuing the models that PLOOTO generated, in an .idf format, do not cause any errors when they undergo a thermal simulation.
- To test the whole process of generating different spatial arrangements (.idf files) and use them as an input to a parametric optimisation tool (jEPlus and jEPlus+EA, in this case).

This study was published in Schwartz et al. (2017) ¹

4.2.2. Methodology and Study Design

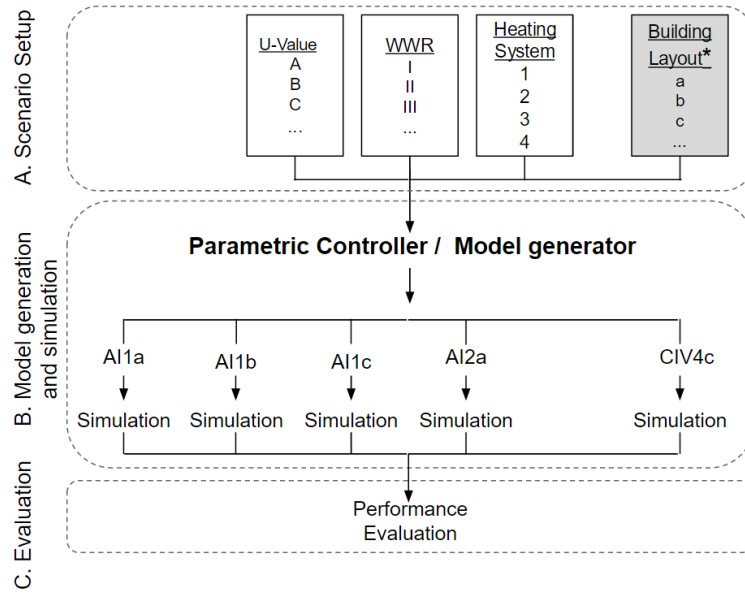
Figure 3.4, (adapted from Zhang, 2012), shows the three steps for carrying out parametric thermal simulation optimisation:

- A. *Set-up*:** A description of the different input parameters. In the example shown in Figure 4.8, each design category (U-Value, WWR and heating system) has numerous possible input parameters. The overall number of possible combinations of input parameters is the model's search space.
- B. *Model Generation and Simulation*:** Once the input parameters are defined, a parameter controller iteratively generates individual models, based on the combinations defined in step A. These models are then simulated using a thermal simulation tool.
- C. *Evaluation*:** Lastly, simulation results are stored, and their thermal performance is evaluated.

In this pilot study, a new concept is introduced and tested – incorporating building layouts (geometric description of the building) to the optimisation procedure, as part of the Set-Up stage, as illustrated by the coloured rectangle in Figure 4.11.

The design of this study is an extension of the study design of the previous pilot study (section 4.1), as seen in Figure 4.12. The study is carried by using the following tools:

- PLOOTO was used for the generation of .idf files with different spatial arrangements.
- EnergyPlus was used for the thermal simulations.
- jEPlus was used as a parametric controller.
- jEPlus+EA was used for executing the optimisation study.



* Building Layout is the new concept that is introduced and tested in this pilot study

Figure 4.11: The steps of a parametric thermal simulation optimisation (Each element in stage E1 is composed by genes from stage D (data inputs). For example, the first element in E1(AI1A) has the 'A' phenotype from U-Value, the 'I' phenotype from WWR, the '1' phenotype from heating system etc.)

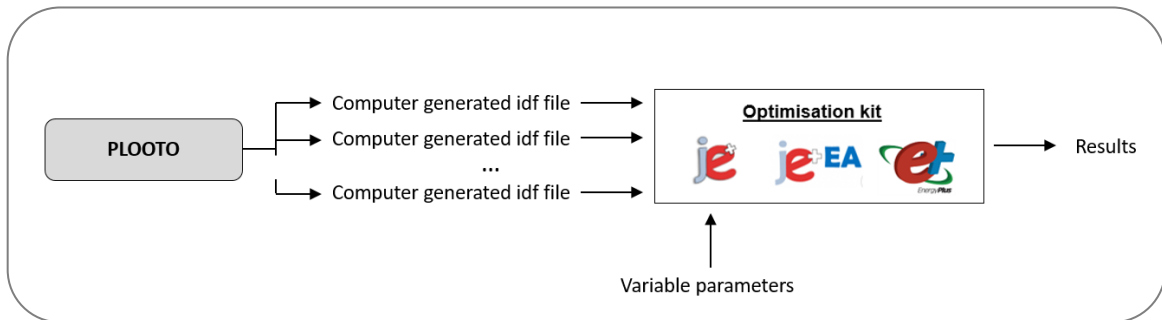


Figure 4.12: Pilot study 2 - study design

4.2.3. Results and Discussion

4.2.3.1. Case 1: Simple Space Division

The first test aims to examine the robustness of PLOOTO by testing its ability to find all possible spatial arrangements of a given design task. To enable this, a simple spatial arrangement task (Figure 4.13 left) was designed, where a set of three rooms with fixed dimensions should be placed on a plot sized 720 x 720 cm. For this particular design task, when the orientation of the model is fixed, only four possible design solutions are possible, as described in Figure 4.13 (right). It took PLOOTO an average of 21 seconds to find all four possible arrangements (overall 10 runs).

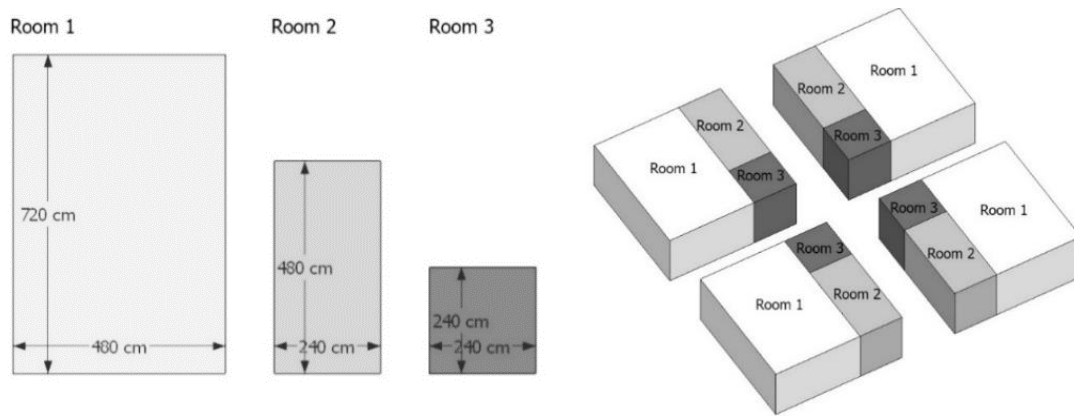


Figure 4.13: The dimensions of the three rooms (left). The four possible spatial arrangements (right)

4.2.3.2. Case 2: Terrace House

a) Model Generation Results

For the second test, a single-family terrace house building was generated and its performance optimised.

As the generated geometries should aim to represent a terrace house, spatial characters of the terrace houses (such as the plot size, number of floors and rooms, possible rooms dimension etc.) had to firstly be identified. Based on work undertaken by Oikonomou et al. (2012), who identified typical dwellings in London, a typical terrace house was determined (Figure 4.14) – the dimensions of the different rooms were set, as well as the size of the plot.

The range of allowed room dimensions, which is one of the main input parameters, is shown in Table 4.5. The wall-to-ceiling height was set to 3.0 meters, and an adjacency matrix, describes the relationships between the different rooms was also established. As the code was designed to identify external walls that touch the edge of the plot, these were defined as adiabatic surfaces that could not have any windows.

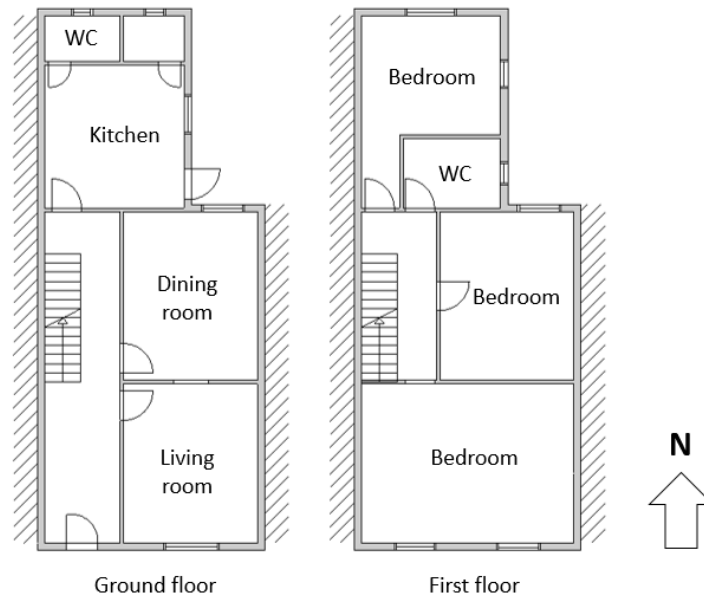


Figure 4.14: a 'typical' London terrace house (Adapted from Oikonomou et al., 2012)

		Width		Length	
		Min	Max	Min	Max
Ground floor	Living	540	600	360	440
	Dining	360	440	360	440
	Kitchen	360	440	360	440
	Core (stairs)	160	240	360	440
1st floor	Bedroom 1	540	600	360	440
	Bedroom 2	360	440	360	440
	Bedroom 3	360	440	360	440
	Core (stairs)	160	240	360	440

Table 4.5: Allowed room dimension range

An overall 15 spatial arrangements were generated and tested (Figure 4.15). Each model consisted of 8 thermal zones, each of which had to have at least one window, but not more than two. Window-to-wall ratios (WWR) could be either 25 or 75%. As this pilot study focused on the geometrical aspects of the EnergyPlus file (spatial arrangements and window-to-wall ratio), each window could be examined independently for its size. All other model inputs were identical (envelope build-ups and materials, rooms schedule, rooms thermostats, occupancy schedules etc.).

Given the 15 models, each with 8 thermal zones with 1 or 2 windows at 2 different possible WWR, the search space in this case had an overall 983,040 possible geometric combinations. The selected optimisation objectives were defined as ‘ideal loads’, for both annual heating and annual cooling. Since the outcome of an optimisation for these objectives can be roughly predicted, it allowed an objective evaluation of the success of the optimisation procedure by comparing the outputs with the anticipated results.

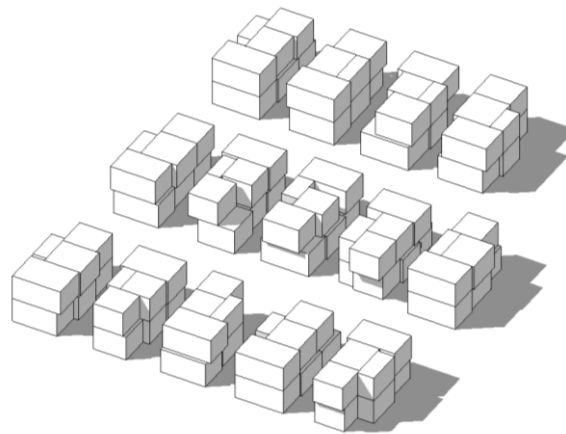


Figure 4.15: The 15 building geometries generated by PLOOTO.

b) Building Optimisation Results

Figure 4.16 (left) shows that using the proposed approach, a pareto-optimal front with 3 optimal models was found. Since this is a relatively simple design task with a simple set of solutions, the system converged quite quickly – after 20 generations (population size of 10 models in each generation).

Figure 4.16 (right) shows the two spatial arrangements with the best performance (black dots) versus the two arrangements with the worst performance (red dots). This indicates that some spatial arrangements performed better than others: As expected, spatial arrangements that had a lower surface area to volume ratio (or, more compact buildings) – resulted with better performance. Table 4.6 shows the external surface area to volume ratio of the best and worst spatial arrangements from Figure 4.16 (right).

For more details and analysis of this pilot study, please refer to the publication “Integrated Building Performance Optimisation: Coupling Parametric Thermal Simulation Optimisation and Generative Spatial Design Programming”.

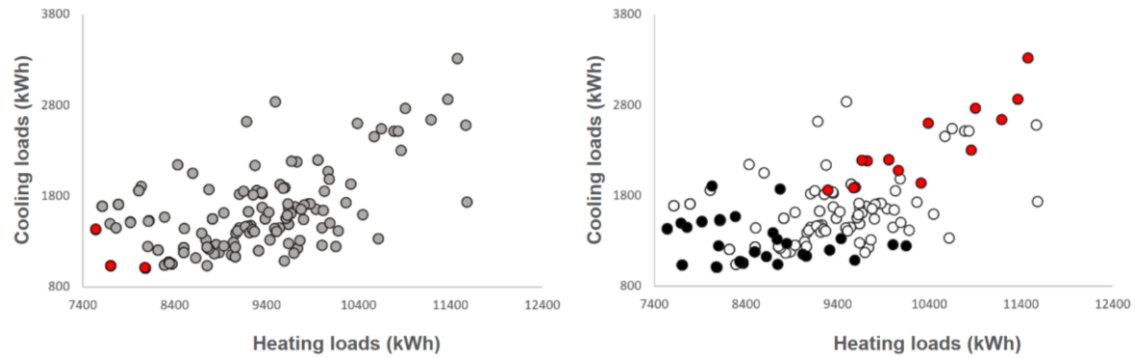


Figure 4.16 Left - Pareto-optimal front of 3 optimal models. Right - The performance of the best and worst models

	Model number	Overall external surface to Volume Ratio	Non-Adiabatic external surfaces to Volume Ratio
Best	10	0.985	0.886
	12	1.024	0.819
	1	1.059	0.795
Worst	6	1.077	0.937
	11	1.077	0.983
	8	1.016	0.95

Table 4.6: Best and worst geometries surface-to-volume ratio

Figure 4.17 shows the best and worst models. As expected, models that had larger surface area (through which heat can be lost) and larger windows (surfaces with worst thermal qualities, compared to windows) – performed worst.

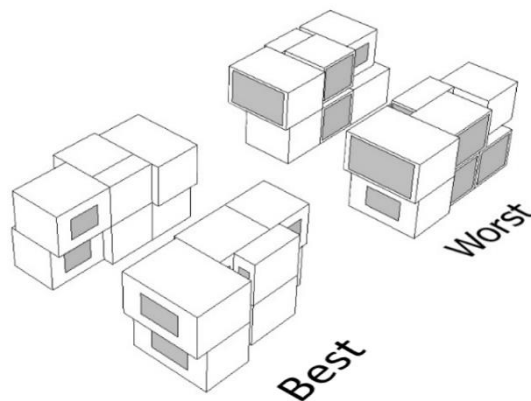


Figure 4.17: Best and worst performing geometries

4.2.4. Findings Summary

	Pilot study findings	Implications for the research
1	<p>PLOOTO was successful in finding all possible design solution for a given design task.</p> <p>PLOOTO found 15 spatial arrangements for a complex design task – that of a terrace house.</p>	<p>Testing and validating PLOOTO's capabilities in finding spatial arrangement.</p>
2	<p>The models PLOOTO generated were used as input parameters in an optimisation study. The models were manually checked to ensure that all surfaces were correctly identified (internal/external/adiabatic etc.). The models were successfully simulated, no errors emerged.</p>	<p>Testing PLOOTO's abilities in generating building models in the format of .idf files with which a full thermal simulation could be conducted with no errors</p>
3	<p>An entire optimisation procedure was successfully implemented</p>	<p>The proposed methodology is tested by running a complete process of automated generation and optimisation of a new terrace house building using PLOOTO as the generative design tool and an existing optimisation tool (jEPlus+EA) for optimisation.</p>

Table 4.7: Pilot study 2 findings summary

4.3. Framework Component 3: The validation of the Designated Parametric Controller and NAGA-II Optimisation Tool

4.3.1. Aim

The aim of the third pilot study was to examine the capabilities of the designated optimisation application that was programmed for the purpose of this research, in the context of LCCF and LCC optimisation, and validate its results and pareto front. To achieve this aim, the following objectives were set:

- Using a designated NSGA-II application, how does its pareto-front compare with that of the entire search space, in terms of LCCF and LCC?
- How does the search space of the designated NSGA-II application compare with that of the same number of random models?

4.3.2. Methodology and Study Design

The design of this pilot study is based on the use of a designated NSGA-II tool to find a set of pareto-optimal solutions, in terms of LCCF and LCC, for a simple optimisation problem: The design of a single-story building in a given plot, using a series of design parameters (build-ups, window-to-wall-ratio, window types etc.), and multiple geometries (which were generated by PLOOTO).

Figure 4.18 illustrates the study design. Firstly, PLOOTO geometries are generated, based on a series of geometric criteria that had been identified in an earlier stage. Following this, three tests are performed to ensure that the NSGA-II results converged to the actual pareto front and that the results are not random:

- 1) a simulation of the entire search space of the optimisation problem (all possible design alternatives).
- 2) an NSGA-II optimisation using the designated application.

3) a random set of simulations, within the same search space of the optimisation (using Monte Carlo). Each of the stage 2 and 3 were carried out three times, to ensure that the simulation outputs were not occasional and to increase the confidence in results. Lastly, the outputs of all three tests are plotted against each other and compared.

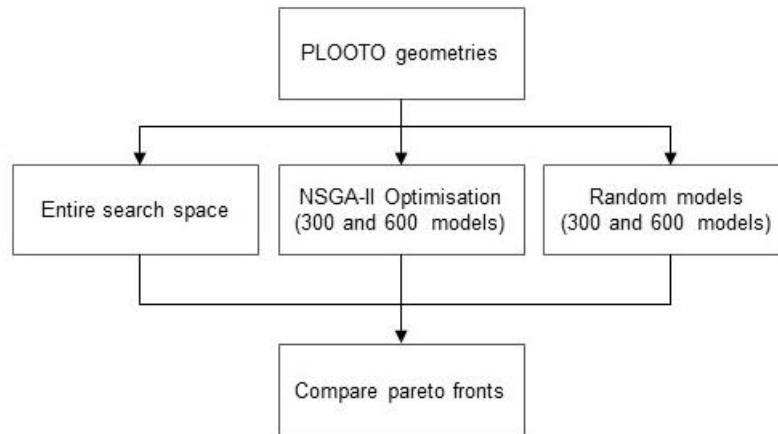


Figure 4.18: Pilot study 3 - study design

To execute this pilot study, the following tools were used (as seen in Figure 4.19):

- PLOOTO was used for the generation of .idf files with different spatial arrangements.
- EnergyPlus was used for the thermal simulations.
- The designated NSGA-II algorithm was used for carrying the optimisation, post processing and plotting procedures.

For the generation for the .idf files, the same geometries that had been generated by PLOOTO and used in section 4.2.3.1 were used. The models' thermal properties (systems, occupancy schedules, internal loads etc.) were all assigned automatically during the generation process. The optimisation objectives (LCCF and LCC) and optimisation controls (mutation, number of generations and crossover rates) were all set in designated NSGA-II tool. The life cycle scope and impact assessment boundaries are described in Table 4.8.

Table 4.9 shows the number of possible values for each input parameter. The size of the search space (i.e., the number of all possible design combinations) in this case is 122,880.

	A1-A3			A4-A5		B1-B7							C1-C4			
	Product stage			Construction		Use							End of Life			
	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4
	Raw material supply	Transport	Manufacturing	Transport	Construction	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction	Transport	Waste processing	Disposal
LCCF	✓	✓	✓	✓	✓				✓		✓	✓	✓	✓	✓	✓
LCC	✓	✓	✓						✓		✓	✓				

Table 4.8: Pilot study 3 life cycle scope (based on BS EN 15978:2011)

Gene number	Name	Possible values
1	Layouts	4
2	Thermal zones (per layout)	3
3	Windows (per thermal zone)	1
4	Window to wall ratio	2
5	External wall build-ups	5
6	Ground floor build-ups	4
7	Internal wall build-ups	2
8	Rood build-ups	3
9	Window types	2
Total Number of combinations		$4 \times 2^{(3+2+2)} \times 5 \times 4 \times 2 \times 3 \times 2 = 122,880$

Table 4.9: Building properties for optimisation and their possible values

The implementation of this pilot study consisted of three steps, as shown in Figure 4.19:

- Modelling and simulation of the entire search space - i.e., 122,880 models (4.14 top)
- Modelling and simulation of a small number of random models (300 and 600 models) using Monte Carlo
- Modelling and simulation of a small number of random models (300 and 600 models) using the NSGA-II algorithm

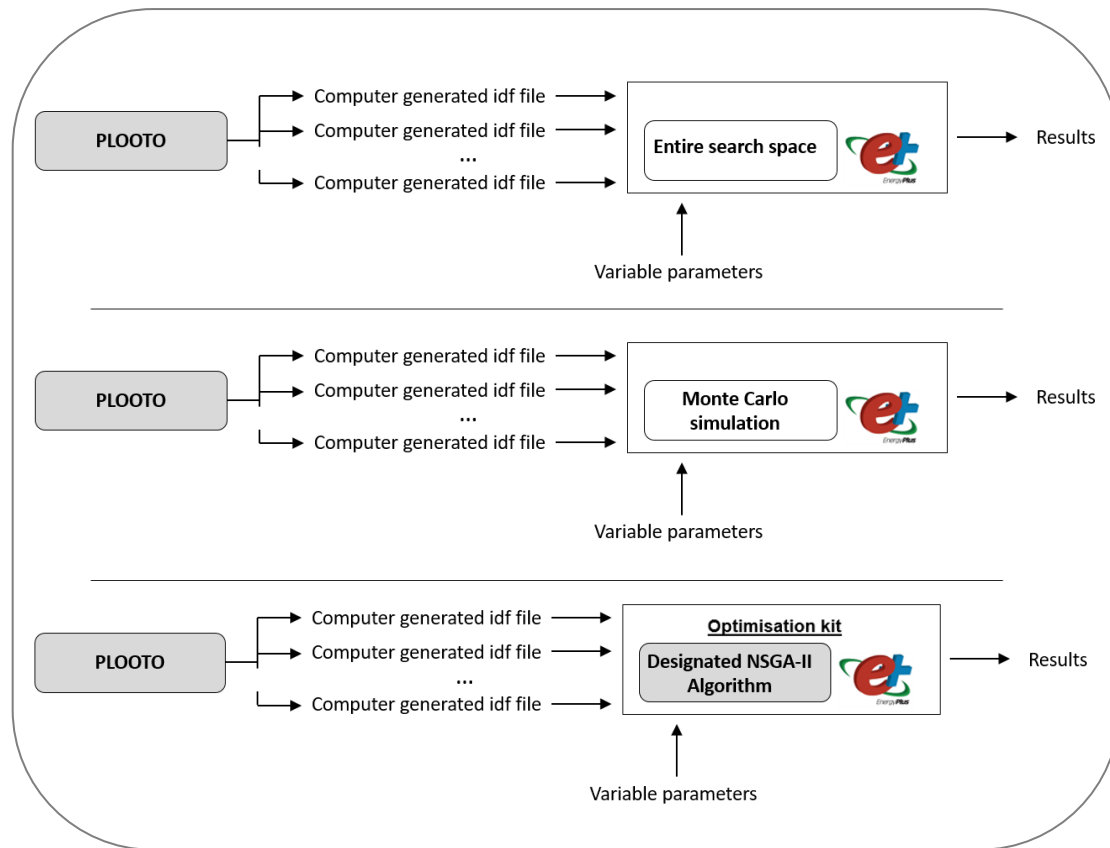


Figure 4.19: Execution - 3rd pilot study

4.3.3. Results and Discussion

Firstly, the entire search space of the optimisation task (122,880 models) was simulated and the LCCF and LCC of each model was plotted (Figure 4.19). Next, two tests were conducted:

a) 10 generations x 60 individuals (600 models)

In this test, a set of three runs was carried out, plotting the performance of 600 random models against that of the entire search space, using Monte Carlo method (Figure 4.20). Following this, a set of three optimisation runs, using the NSGA-II application, was carried out, and the performance of its 600 models (10 generations, 60 models per generation) was plotted against the entire search space (Figure 4.21).

Results suggested that while the output of the random models spread quite equally across the search space, the NSGA-II models did manage to converge towards the true pareto

front. Moreover, the results indicate that the NSGA-II managed to find both local and global optimums, without being trapped in the local optima solutions.

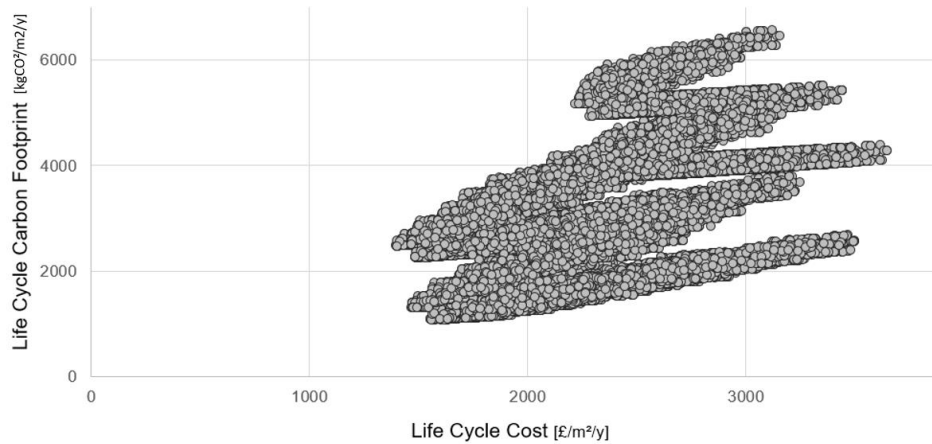


Figure 4.20: The LCCF and LCC results of the entire search space

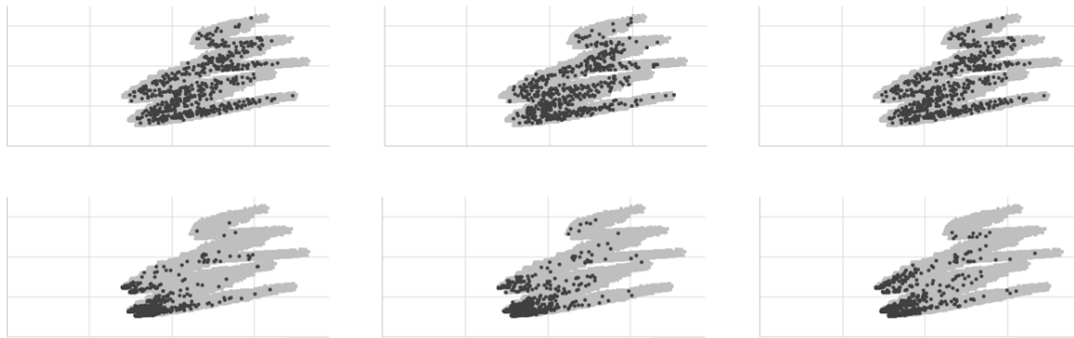


Figure 4.21: The LCCF and LCC of 600 random (Monte Carlo) models, laid over the entire search space (top), and the LCCF and LCC of 600 (10 generations, 60 models) NSGA-II models, laid over the entire search space (bottom).

b) 10 generations x 30 individuals (300 models)

The next test aimed to examine the effect of a smaller population size, i.e., 30 individuals per generation, compared to the previous 60 individuals. Therefore, another set of three runs was carried for 300 random models, and 300 models (10 generations, 30 models per generation) using the NSGA-II application, as seen in Figure 4.22. Results showed that even when using as little as 300 models (less than 0.25% of the search space), the NSGA-II optimisation had converged, compared to the random simulations, and managed to find the optimal pareto front while avoiding a 'local optima' trap. These results indicate that the optimisation application is robust, and that its outputs are not random.

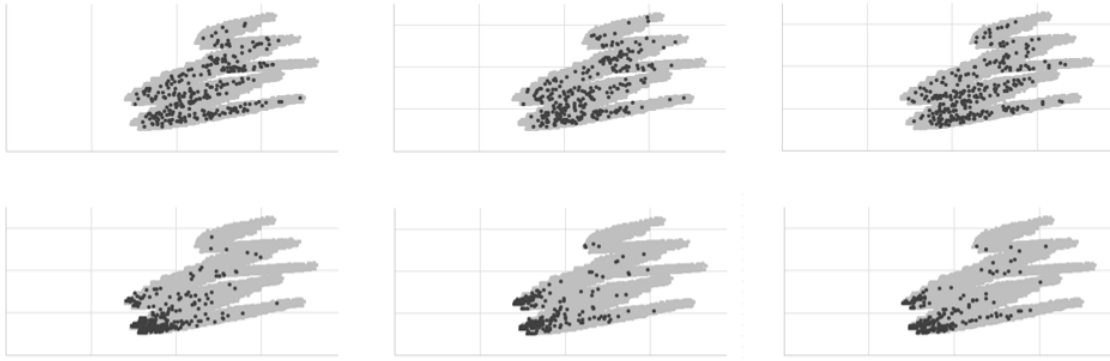


Figure 4.22: The LCCF and LCC of 300 random (Monte Carlo) models, laid over the entire search space (top), and the LCCF and LCC of 300 (10 generations, 300 models) NSGA-II models, laid over the entire search space (bottom).

4.3.4. Findings summary

Pilot study findings	Implications for the research
<p>1 The results of three optimisation runs, using a designated optimisation algorithm, were compared to the simulation results of the entire search space. The study showed that the optimisation results successfully converged, and that its pareto front was identical to that of the brute force. The algorithm managed to find the global optimal solution, without getting trapped in local optimal ones.</p>	<p>This ensures that the tailored NSGA-II algorithm works properly and that it was successful in finding a set of pareto-optimal results.</p>
<p>2 The results of the optimisation procedure were compared to the same number of random simulations, to ensure that the convergence is the result of the algorithm rather than random. The study clearly showed different patterns in the search space, when the optimisation and random results were plotted against each other, which indicated that the convergence is not random.</p>	<p>This ensures that the tailored NSGA-II algorithm works properly, and that the convergence is not random</p>

Table 4.10: Pilot study 3 findings summary

4.4. Developing the Computational Framework - Summary

In this chapter, the proposed computational framework for this research was established, and its different components were developed, tested and validated.

Since some parts of the proposed framework components have never been used in the research of the built environment, and as others were developed especially for this research, the testing and validation steps provided valuable insights for the development of the research design.

The first study examined the core of the research approach - using an optimisation algorithm to find an optimal design for a refurbishment project. Using an 'of-the-shelf' NSGA-II optimisation tool, the results of this study indicated that the proposed method can successfully find optimal design alternatives.

The second study explored the potential of coupling a designated computational generative design algorithm (PLOOTO) with an NSGA-II optimisation tool and thermal simulation application. The pilot study results highlighted that the proposed generative design algorithm successfully found numerous building design alternatives, and showed the successful integration between spatial arrangements and the optimisation framework, which resulted with a series of pareto-optimal models.

The last study aimed to test the entire flow of generating optimal buildings, and validate the results of a designated NSGA-II optimisation application. This was done by searching for an optimal design of a new simple building. The validation was carried out by comparing the plotted output of the optimisation runs against those of the entire search space, as well as against a set of random models, to ensure the outputs were not random. Results indicated that the proposed NSGA-II algorithm successfully found a set of pareto-optimal designs.

Once all three studies had been tested and showed satisfied results, the proposed framework and tools could be used to test the main research case studies.

Chapter summary:

- The proposed computational framework of this research was developed, tested and validated in this chapter. Since parts of the proposed method have never been applied in the context of research of the built environment, the testing and validation of the proposed framework were essential, to ensure it can be used in this research.
- The examination of the computational framework was carried out by dividing the proposed approach into three components, and by examining their implementation using pilot-studies
- The three components that had been tested are:
 - A complete refurbishment scenario: This aimed at testing, for the first time, the fundamental principle of using optimisation methods in the case of refurbishments of existing building, using thermal simulation tools and life cycle performance, to find optimal design solutions.
 - A complete replacement scenario: This included the automatic generation of various designs of a terrace house, in an EnergyPlus .idf format, using a designated application (PLOOTO). A new optimisation approach was then tested: The integration of the generated designs was coupled with an 'of-the-shelf' optimisation application (jEPlus+EA).
 - The validating the results of a tailored NSGA-II optimisation algorithm was carried out by comparing the plot and pareto front of an entire search space with those of the tailored optimisation application.
- All pilot studies resulted with satisfying outcomes, which ensured the complete computational framework can be used, and that the proposed research design and methodology can be applied in this research.

5. Implementation of the Proposed Framework

Following the evaluation of current literature and the development and testing of the proposed computational framework, this chapter presents the results of the life cycle performance analysis for the refurbishment and the replacement scenarios for the selected case study buildings. The chapter begins with an introduction of the execution framework, the analysis scope and the common case study assumptions. This is followed by a detailed description of each case study building and the execution of the optimisation for each design scenario. Main findings are then analysed and discussed, and a set of comparisons between the optimal designs is carried out.

5.1. Research Implementation

5.1.1. Analysis Structure

The analysis of all case studies was carried out using the same format. The structure of the analysis is described in Figure 5.1:

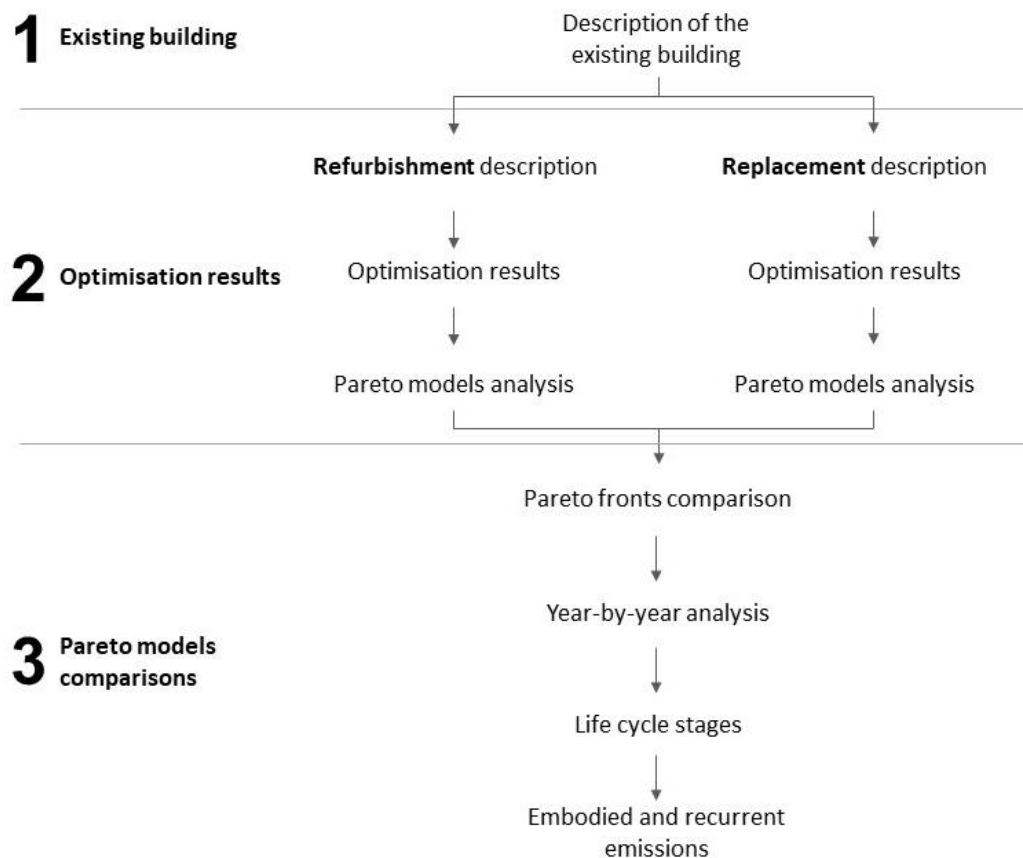


Figure 5.1: Study execution

1. Description of the Existing Building

In this section, drawings of the existing building are presented, and an initial set of analysis assumptions are discussed.

2. Optimisation Results: Refurbishment / Replacement Scenarios Analysis

In this part, the optimisation of each design scenario is executed independently, and the optimisation results are displayed. This section includes the following sub-sections:

- a. Model description: This includes the description of the design scenario – the distribution of the buildings thermal zones and potential windows orientations (all models were simulated under the assumption that there could be only one window per thermal zone).
- b. Optimisation results: In this section, the LCCF and LCC pareto-optimal fronts are presented, as well as the progress of the NSGA-II optimisation towards conversion. For validation and verification purposes, three sets of optimisation runs were carried out for each case study. Only the first case study, though, presents the results of all three optimisation runs. The following case studies showed only one set of results.
- c. Pareto models analysis: This part includes an analysis of the pareto front models. Some of their shared properties are discussed, as well as some major differences.

3. Pareto Models Comparison

In this section, a set of comparisons and analysis are carried out between the optimal refurbishment models and the optimal replacements. These included:

- a. A pareto fronts comparison: The pareto fronts of the two design scenarios are plotted against each other in this sub-section, and a comparison between the performance of the mean optimal models is carried out.

- b. Year-by-year analysis of emissions and costs: A comparison between the annual aggregated CO₂ emissions and cost is then carried.
- c. Life cycle performance breakdown: In this analysis, a comparison between the two design scenarios is carried in respect of the impact of each stage in their life cycle (construction, operational energy consumption, domestic hot water heating etc.).
- d. Embodied CO₂ and embodied cost breakdown: A comparison, examining the contribution of each building component to the overall building embodied CO₂ and initial capital investment, is then presented.

5.1.2. Pareto-edge Models

The concept of Pareto-edge models (Figure 5.2) is introduced to enable a clearer analysis of the pareto front: Typically, the two most distant models on the pareto front share the least common modeling properties. The pareto-edge models are named ('Model 1' and 'Model N' in Figure 5.2). The analysis of their performance enables better understanding of the performance of other models on the pareto front. Furthermore, the use of this technique makes the comparison between the two design scenarios (refurbishments and replacements) easier and opens a new opportunity for communicating the comparison results.

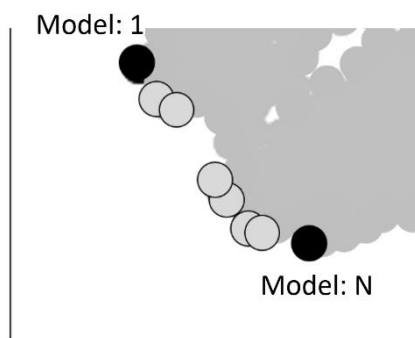


Figure 5.2: Pareto front (light gray) and Pareto edge models

5.1.3. Goal and Scope

The case study buildings life cycle scopes are described in Table 5.1, for both LCCF and LCC. The scope description is based on the BS EN 15978:2011 – sustainability of construction works framework. Sources of CO₂ emissions and costs data for the different building components and materials throughout the buildings life cycle stages are presented Tables 5.2, 5.3, Appendix A and Appendix B.

	A1-A3			A4-A5		B1-B7							C1-C4			
	Product stage			Construction		Use							End of Life			
	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4
	Raw material supply	Transport	Manufacturing	Transport	Construction	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction	Transport	Waste processing	Disposal
LCCF	✓	✓	✓	✓	✓				✓		✓	✓	✓	✓	✓	✓
LCC	✓	✓	✓						✓		✓	✓				

Table 5.1: Study life cycle scope (based on BS EN 15978:2011)

LCCF Stage	Data source and references
A1 - A3	EPD ¹ , Bath ICE. Geometries based on the .idf (replacement rates and waste rates applied ¹)
A4	3% from overall Embodied CO ₂ *
A5	7% from overall Embodied CO ₂ *
B1-B3	Out of the scope of this research**
B4	EPD ¹ and Bath ICE. Assumed life expectancy ¹
B5	Out of the scope of this research**
B6	Space heating - EnergyPlus simulation. Electricity for lighting – manual calculation
B7	Based on Energy Saving Trust (2008)
C1 - C4	2% from overall Embodied CO ₂ *

Table 5.2: Sources of data for the CO₂ emissions involved in the different life cycle stage

¹ Please refer to Appendices A, B and F

LCC Stage	Data source
A1 - A3	Building components and materials cost ¹ Geometries based on the .idf (replacement rates and waste rates applied ¹)
A4-A5	Out of the scope of this research***
B1-B3	Out of the scope of this research**
B4	EPD ¹ and Bath ICE. Assumed life expectancy ¹
B5	Out of the scope of this research**
B6	Space heating - EnergyPlus simulation. Electricity for lighting – manual calculation
B7	Based on Energy Saving Trust (2008)
C1-C7	Out of the scope of this research***

Table 5.3: Sources of data for the costs involved in the different life cycle stage

** Based on Cole & Kernan (1996), Blengini & Di Carlo (2010), Dixit et al. (2010), Gustavsson et al. (2010) and Monahan & Powell (2011)*

*** B1–B3: The building types in this research are simple (private residential, compared to high-maintenance office buildings) and require minimal maintenance (mainly cleaning or other maintenance actions) and repair (fixing of unpredictable failures within the building and its systems) that should not have a significant impact on the case study's LCCF.*

B5: Refurbishment is the alteration of the physical characteristics of the building, to cater it for future function. It is assumed that the case study buildings will be used as residential buildings throughout their lives.

**** A1-A4 and C1-C7 are all related to the cost of labour, which is excluded from this research as it can differ significantly across contractors.*

5.1.4. Life Cycle Impact Assessment

The evaluation of the LCCF and LCC of each model was carried out automatically by the NSGA-II application. The application identifies the relevant modelled building materials and their quantities, and then adds up their associated embodied CO₂ and costs factors (including CO₂ incurred by replacements, waste, transportation etc., as described in Tables 5.2, 5.3 and Appendices A and B). Once the thermal model undergoes an EnergyPlus simulation, the algorithm retrieves the model's energy consumption, assigns the relevant operational CO₂ and costs values to it and adds these values to those of the embodied CO₂ and costs.

Following the study scope, LCCF and LCC were calculated using the following formulas:

Please refer to Appendices A, B and F ¹

$$LCCF = \sum_{Ei}^i (Eip + Eit + Eic + Eir + Eio + Eieol + Ere) \quad (1)$$

Where:

LCCF = Life Cycle Carbon Footprint (kgCO₂/m²/y)

i = Model number

Eip = Emissions due to overall building materials production and manufacturing

Eit = Emissions due to transport to site

Eic = Emissions due to construction works on site

Eir = Emissions due to replacements works

Eio = Emissions through the operational stage of the building (lighting, space and water heating)

Eieol = Emissions through the End of Life stage and disposal of the building

Ere = Emissions of elements that had been removed (embodied CO₂ of original building component)

$$LCC = \sum_{Ci}^i (Cip + Cir + Cio) \quad (2)$$

Where:

LCC = Life Cycle Cost (£/m²/y)

i = Model number

Cip = Cost of overall building materials

Cir = Cost related to replacements works

Cio = Overall cost of the operational stage of the building (lighting, space and water heating)

5.1.5. Life cycle Inventory**5.1.5.1. The Existing Buildings**

This research aimed to compare the refurbished and replacement life cycle performance of the most common residential buildings in the London area. Oikonomou et al. (2012) identified fifteen of the most common London-based residential building archetypes, which represent around 76% of the London housing stock. Buildings types with occurrences of less than 1.5% were excluded from the list. Of the fifteen buildings, nine ‘geometric archetypes’ were identified.

For the purpose of this research, three ‘geometric archetypes’ were selected to be used as case studies. The selection of these archetypes was based on a combination of how

common these buildings in the London housing stock, how different they are, in terms of their layout, spatial arrangement and topology, and based on expected difference in their thermal performance (due to their surface area / volume ratio, or the potential heat loss through their fabric). The three selected archetypes are:

A. A mid-row Terrace House.

This is a two-storey building. The living space, kitchen and dining room are placed at the ground floor, while the bedrooms are located at the first floor.

The main thermal characteristic of this building archetype is that it shares two partitions (party-wall) with its neighbouring buildings. In thermal modelling, it is assumed that these walls are adiabatic. This building has only three exposed surfaces – its roof and its front and back facades.

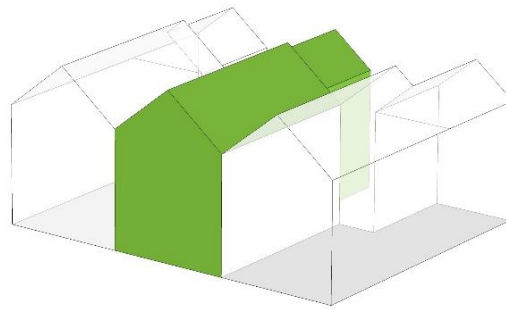


Figure 5.3: Terrace house and its exposed surfaces

B. A Bungalow House.

This is a single-storey building – all rooms are placed on the ground floor level. A bungalow house is a stand-alone structure. This means that all of its external walls are exposed to the local external climate conditions, and heat transfer occurs from throughout its entire envelope.

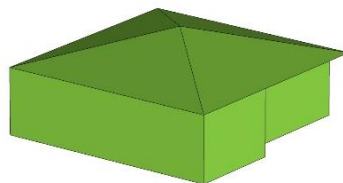


Figure 5.4: Bungalow and its exposed surfaces

C. Block of Flats.

A block of flats is a multi-storey building which contains multiple single-storey residential units, one on top of the other. The top and bottom surfaces of a residential unit in a block of flats is typically shared with its neighbouring units and treated as an adiabatic surface in thermal modelling. The archetype has multiple variations, in which the number of exposed surfaces might vary from one to three.

In this case, to evaluate a more realistic replacement scenario, it was assumed that the existing block of flats is demolished replaced by a more contemporary building type – a “Point-block” (a building with a vertical core at its centre). It is acknowledged that replacement scenario in practice, in an aim to maximise their profit - developers try to increase the number of units they build, often on the account of the unit height and occupants comfort. While acknowledging this as a controversial issue, it was decided to examine realistic scenarios by assuming that replacement buildings will be five storeys high, 2.5m floor-to-ceiling (compared to the original four storeys, 3m floor-to-ceiling).

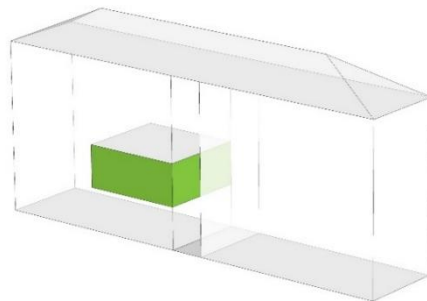


Figure 5.5: Block of flats and its exposed surfaces

It is assumed that in terms of building materials, the existing residential buildings had similar build-ups for most of their surfaces (University of West England, 2018). The assumed build-ups for the original case studies are presented in Table 5.4. It is assumed that the structure of the buildings is a mix of concrete (for the ground floor slab, vertical cores and columns) and timber (internal walls, roofs and external walls sub-structure).

The build-ups of the original buildings were used for the calculating the embodied CO₂ of the existing building elements (termed ‘*Replacement of existing elements*’ in the text).

These are taken into consideration as a preliminary “demolition” of existing building elements (in the case of a refurbishment), or of the entire building (in case of a replacement). These demolitions are inseparable from the analysis, as they allow for the refurbishment or the replacement to take place, and without them – new construction could not be carried out.

For the refurbishment scenarios, it is assumed that structural external brick walls, ground floor screed and all timber constructions (highlighted elements in Table 5.4) are kept untouched, and all other materials are replaced. The embodied CO₂ in the replaced components is added to the LCCF analysis.

For the replacement scenario, it is assumed that the entire existing building is demolished and removed, hence the embodied CO₂ of the entire building is added to the LCCF analysis.

It is also assumed, for both refurbishment and replacement, that a gas boiler will be used for space and water heating. It is assumed that the gas boiler efficiency at the time of installation is 93%, its annual efficiency reduction is 1% and that its life span is 15 years (For further assumptions regarding LCCF and LCC – please refer to Appendix F).

External wall	Internal wall	Internal floors	Ground floor	Roof	Windows	Structure
Brick + structure	Render	Render	Ground	Roof Slate	Single glazed	Reinforced
Plasterboard	Plasterboard	Plasterboard	Screed	Sub-structure	timber frame	Concrete,
Render	Mineral Wool	MDF + structure	Sub-structure	Plasterboard		Timber joists
	Sub-structure	Hardwood	Hardwood	Render		at 40 cm
	Plasterboard					intervals
	Render					

Table 5.4: Existing buildings build-ups (materials that were kept in the refurbishment scenario are highlighted)

5.1.5.2. The Refurbishment Scenario

The refurbishment scenario in each case study is based on the same layout as that of the existing building. As part of the optimisation process, a variety of build-ups is suggested,

each with different embodied CO₂ and cost values. The alternative build-ups for the refurbishment scenarios are described in Figure 5.6. The highlighted building elements were retained from the original building. This means that the embodied CO₂ of these material was not taken into account when carrying the LCCF analysis.

The numbers and letters next to the names of the building materials (e.g., slate **(2)** or EPS **(c)** in Figure 5.6) are used as a legend for the “gene pool table” (Appendix C) – where the build ups that were used in the refurbishment optimisation runs are described.

It is important to note that each build-up alternative, for both the refurbishment and replacements scenarios, was made to meet at least the minimal relevant standards: The standards for improving retained thermal elements, as described in approved document L1B: Conservation of fuel and power in existing buildings (HM Government, 2010) for the refurbishment scenario, and the notional building parameters (Table 4 in Part L1A), as stated in approved document L1A: Conservation of fuel and power in new dwellings (HM Government, 2016). For a detailed description of the different refurbishment building components, occupancy schedules, energy emissions and costs, inflation rates and other simulation assumptions – please refer to Appendices C – F.

5.1.5.3. The Replacement Scenario

For the replacement scenario, it is assumed that the entire existing building is removed. For the optimisation procedure, numerous build-ups are defined, based on input from the industrial supervisor (HB), as described in Figure 5.7.

For a detailed description of the different refurbishment building components, occupancy schedules, energy emissions and costs, inflation rates and other simulation assumptions – please refer to Appendices C – F.

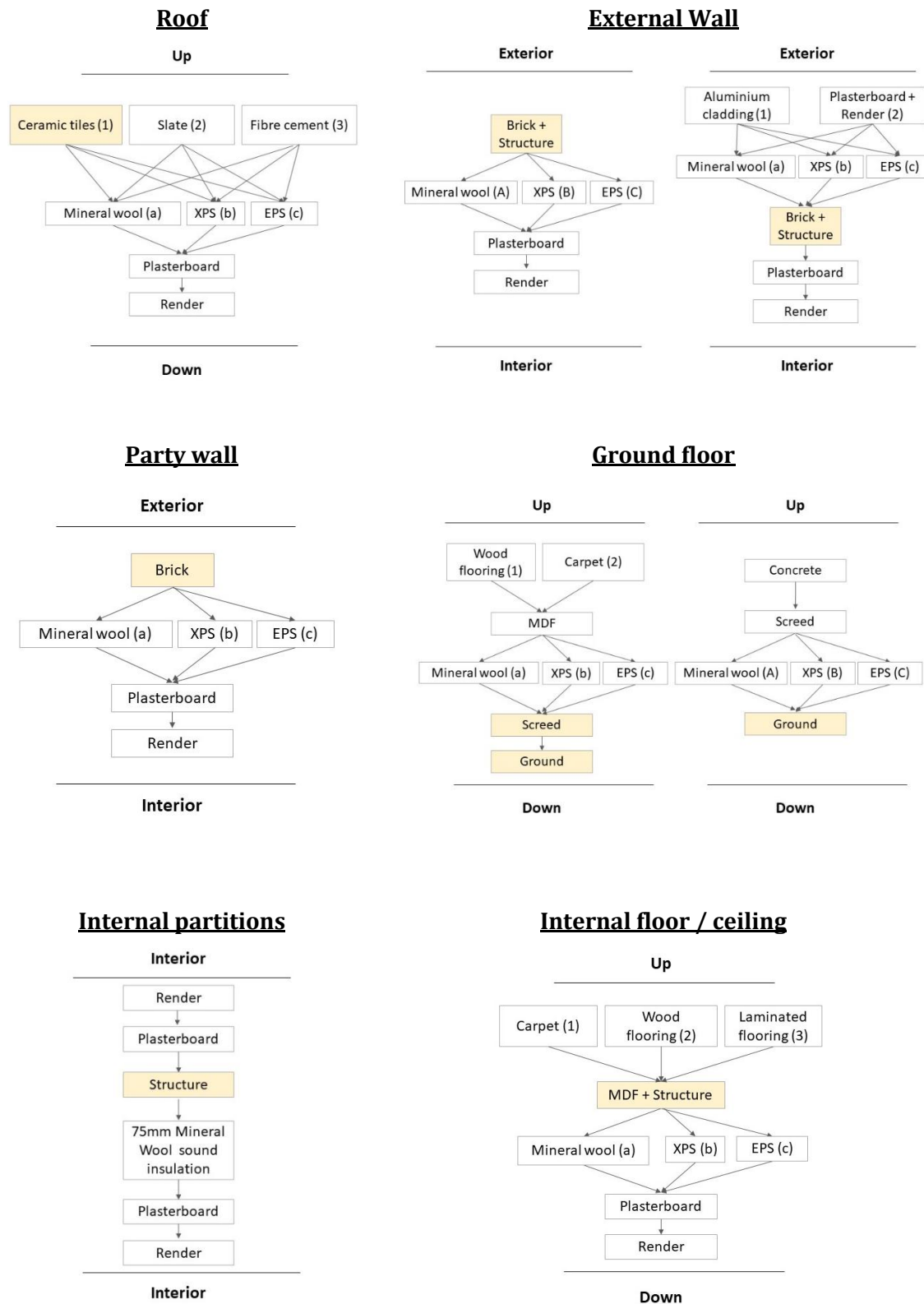


Figure 5.6: Refurbishment scenarios alternative build-ups

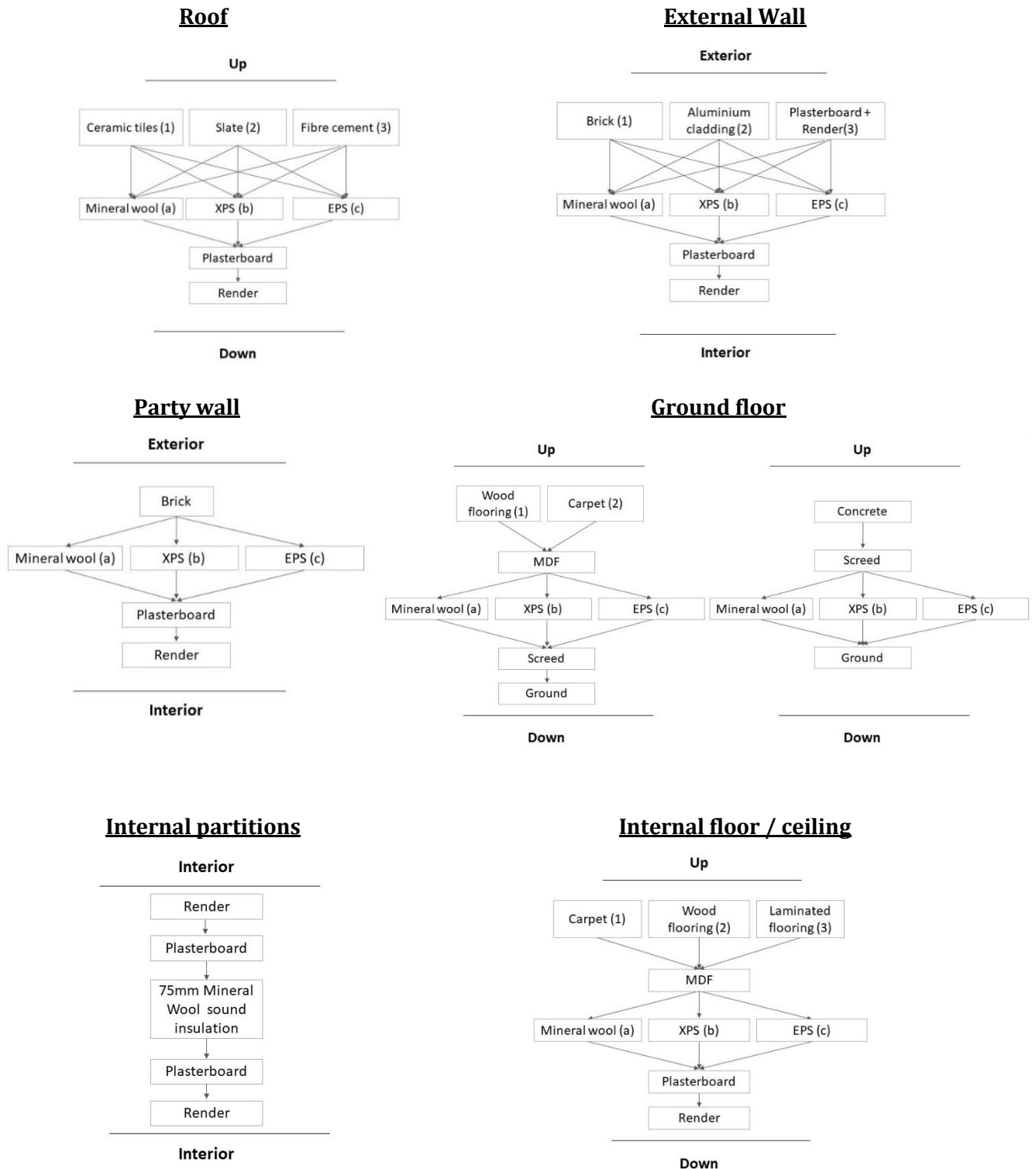


Figure 5.7: Replacement scenarios alternative build-ups

5.2. Case Study 1 – Terrace house

5.2.1. The Case Study Building

The first case study analysis shows a comparison between the LCCF and LCC of the refurbishment and replacement of a prototype of a typical London terrace house. Based on work undertaken by Oikonomou et al. (2012), the floor plans of the original house are shown in Figure 5.8. A description of the existing building constructions and build-ups and the analysis assumptions are described in sections 5.1.3 – 5.1.5 and Appendices C-F.

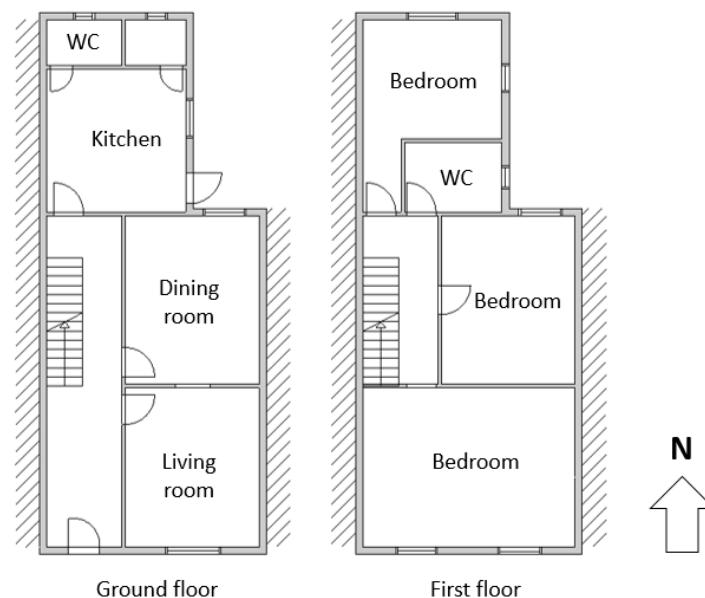


Figure 5.8: Case study 1 - A 'typical' London terrace house (Oikonomou et al., 2012)

5.2.2. Design Scenarios

A. The Refurbishment Model

For the thermal simulations and optimisation process, the case study building was divided into separated thermal zones, as shown in Figure 5.9. Windows could only be installed on external walls which are also non-partition wall. Potential walls for window installations are also shown in Figure 5.6.

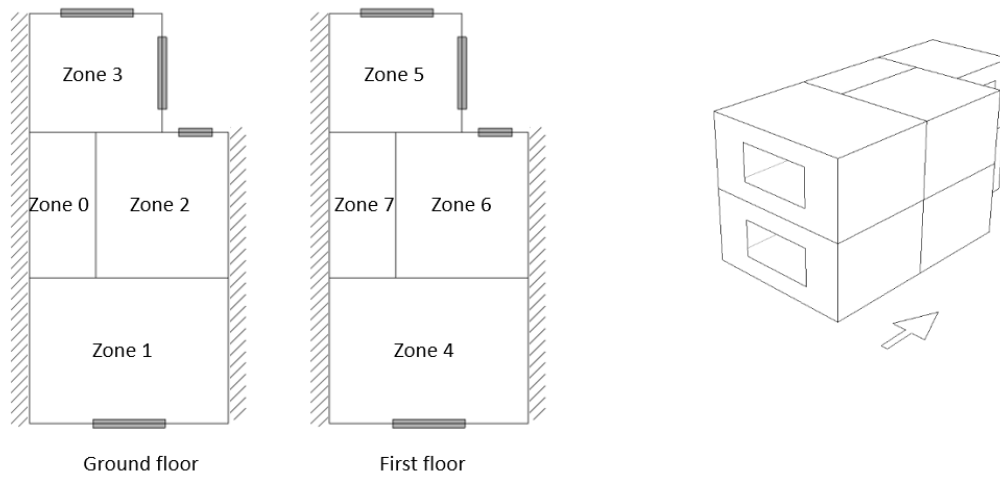


Figure 5.9: Case study 1 – Thermal zones and potential windows orientation for the optimisation of the terrace house refurbishment

B. The Replacement Models

For the life cycle impact assessment of the replacement buildings, new building designs had to be generated and their performance had to be evaluated. Any new design had to be of a similar program, size and volume as those of the original existing building. Therefore, possible room dimensions were identified based on the original building, and a proximity matrix was set to describe room adjacencies (as shown in Table 5.5). These inputs were then inserted to PLOOTO for the generation of different floor layouts and spatial arrangements. PLOOTO was stopped once it reached 32 buildings, as it was noticed that designs typologies started to repeat, and as there were marginal differences between new models.

Thermal Zone			Width		Length		Adjacent to room
			Minimum	Maximum	Minimum	Maximum	
Ground floor	1	Living	600	600	360	440	4
	2	Dining	360	440	360	440	3, 4
	3	Kitchen	360	440	360	440	2, 4
	4	Core (stairs)	160	240	360	440	1, 2, 3,
1st floor	5	Bedroom 1	600	600	360	440	8
	6	Bedroom 2	360	440	360	440	8
	7	Bedroom 3	360	440	360	440	8
	8	Core (stairs)	160	240	360	440	5, 6, 7

Table 5.5: Case study 1 - PLOOTO inputs – possible room sizes and proximity matrix

The 32 buildings which were generated by PLOOTO can be seen in Figure 5.10. It is noted that the layout of the original building was also found by PLOOTO. This means that a scenario in which the existing building is demolished and replaced by a new building of the same layout was also examined.

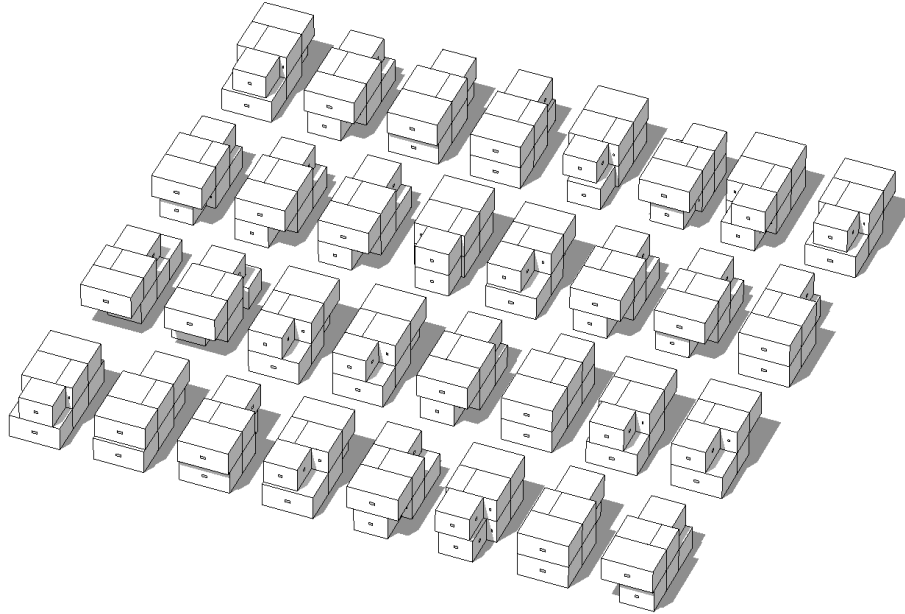


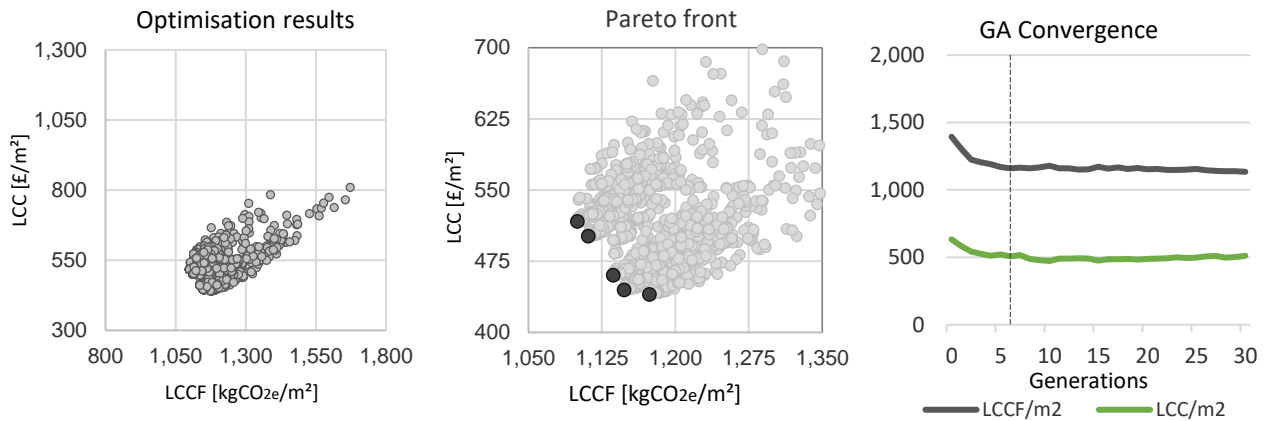
Figure 5.10: PLOOTO outputs – the 32 new-build terrace house designs

5.2.3. Optimisation Results and Pareto Fronts

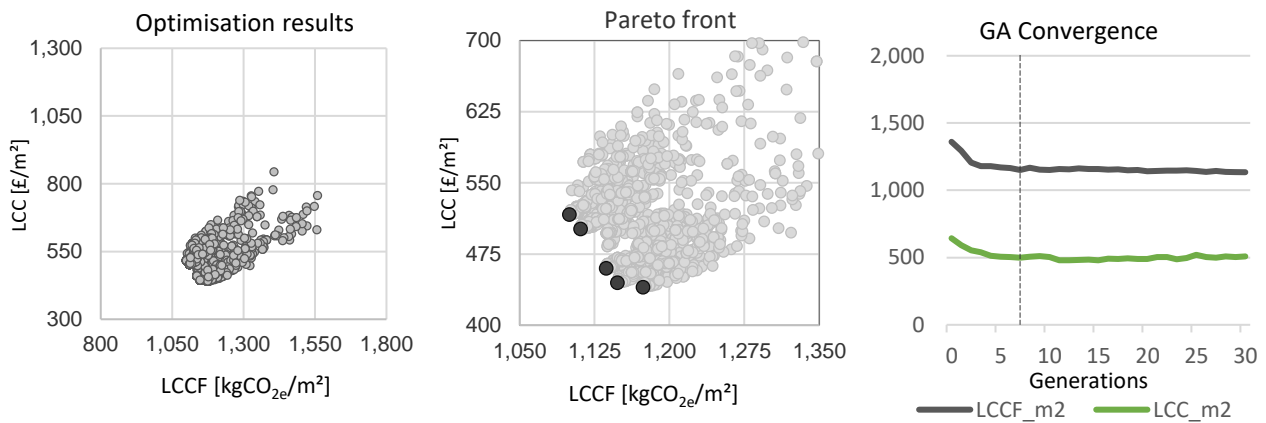
A. Refurbishment

As described in 5.1.1., for verification purposes, three optimisation runs were carried out and analysed. The results of all three runs are presented below (Figure 5.11). Results indicate that all three optimisation runs reached similar search spaces and an identical of pareto front (with 5 pareto-optimal models). The LCCF range of the pareto-optimal models is between around 1,100 – 1,170 kgCO_{2e}/m², and the range of LCC is between 440 – 510 £/m² – aligned with the literature results (section 2.3.3). An examination of the GA convergence rate shows that the systems converged after between 7 to 8 generations.

1st run



2nd run



3rd run

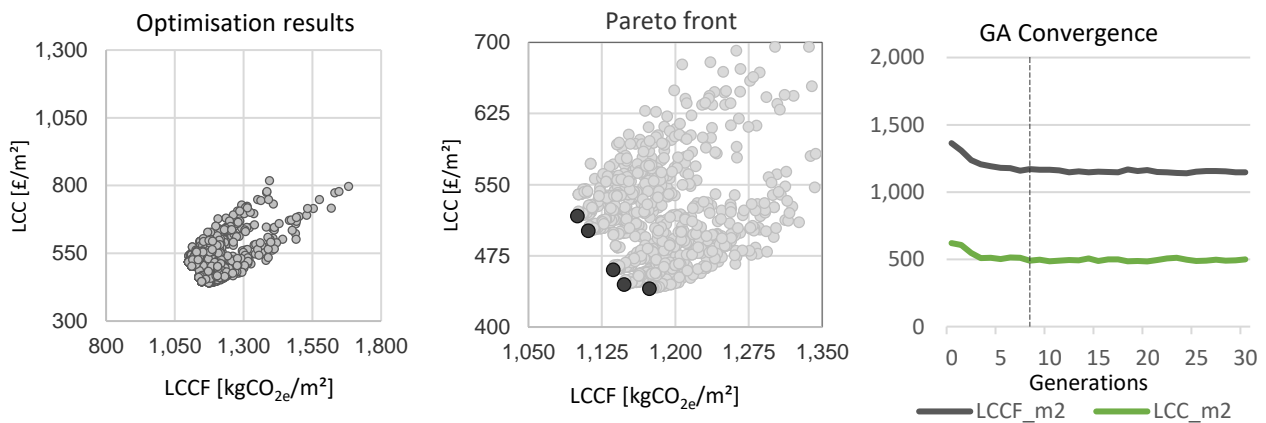
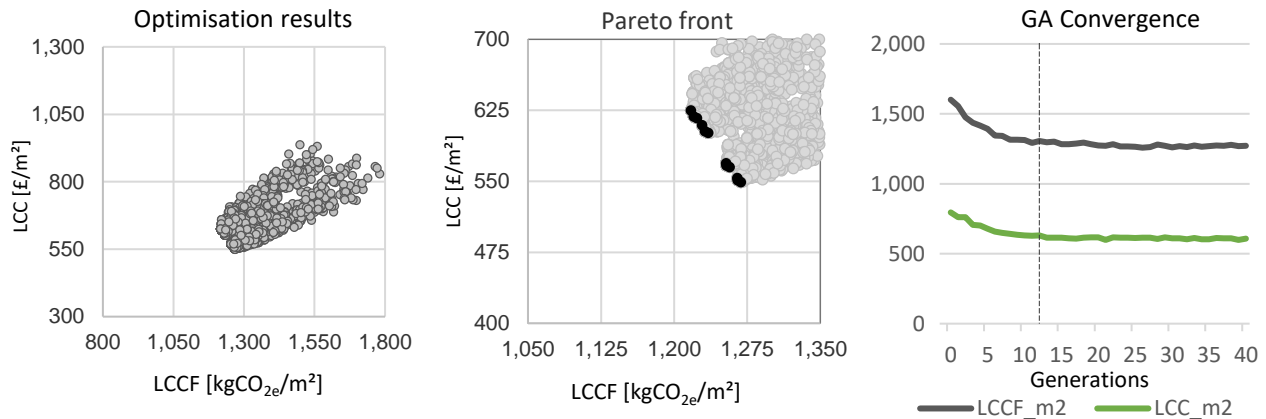


Figure 5.11: Terrace house refurbishment results – LCCF/LCC for 60 years, pareto front and GA convergence

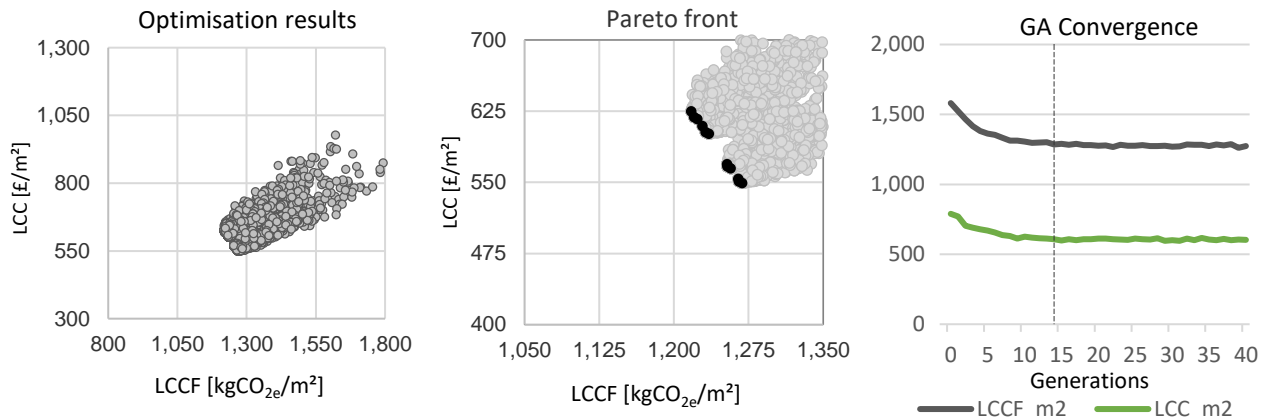
B. Replacement

Figure 5.12 shows that all three replacement optimisation runs have reached similar search space and the same pareto front (12 optimal models). Pareto-optimal models' LCCF ranges between around 1,220 – 1,270 kgCO_{2e}/m², and the LCC ranges between 550 – 620 £/m² - aligned with the literature results (section 2.3.3).

1st run



2nd run



3rd run

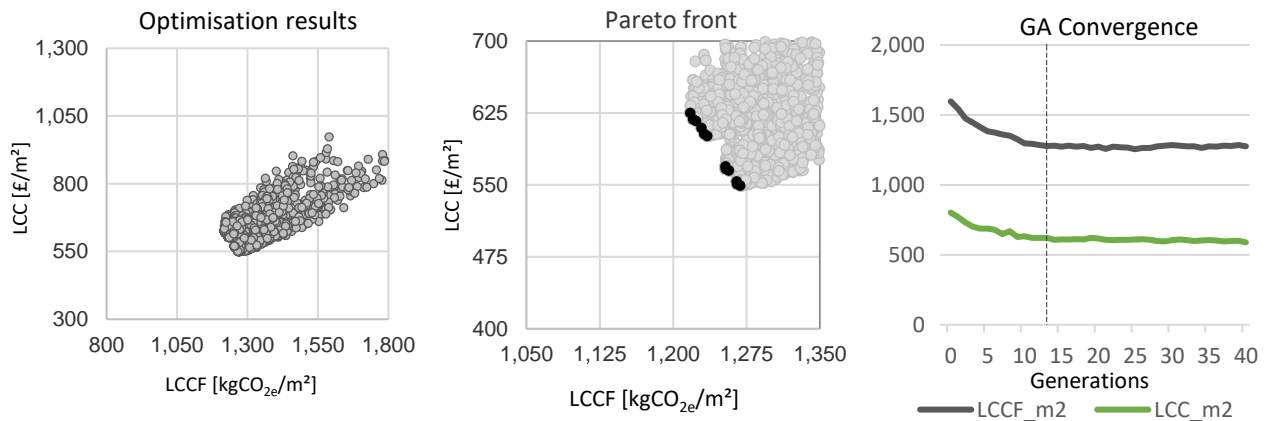


Figure 5.12: Terrace house replacement results – LCCF/LCC for 60 years, pareto front and GA convergence

C. Pareto-Fronts Comparison

A comparison between the pareto fronts of the refurbishment and replacement scenarios (Figure 5.13) shows that under the analysis scope and the constraints of this study, the optimal refurbishments is found to be favourable: The average optimal refurbishment reaches around 10% lower carbon footprint values, and achieved around 20% lower life cycle costs compared to those of the optimal replacements (average refurbishment and replacement LCCF values: 1,134 and 1,244 $\text{kgCO}_2\text{e}/\text{m}^2$ respectively. Average refurbishment and replacement LCC values: 473 and 586 $\text{£}/\text{m}^2$ respectively, $n_1=5$, $n_2=12$, $P<0.05$ for both averages).

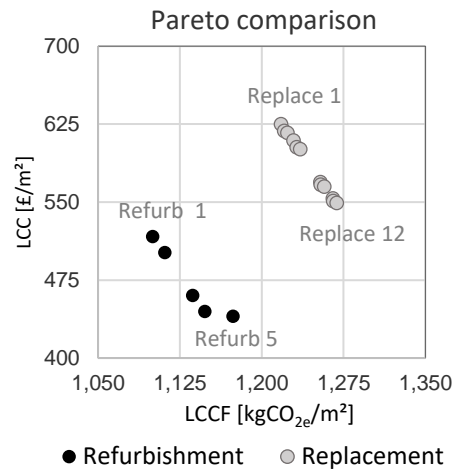


Figure 5.13: Refurbishment vs Replacement: Pareto models comparison

5.2.4. Pareto Models Analysis

A. Refurbishment

An examination of the refurbishment pareto-optimal models (Figure 5.14) shows that all models had the same partition wall, floor/ceiling and ground floors build-ups. Furthermore, all zones had the same window orientations and minimal WWR (25%) throughout the building. The existing building design had a narrow choice for windows orientations, so that the living room, dining room and two bedrooms had a single window orientation, while the kitchen and the one of the bedrooms could have various orientations. In the optimal models, those rooms had east-facing windows. The optimal

model differed with their external wall and roof build-ups, as well as with their window frame materials.

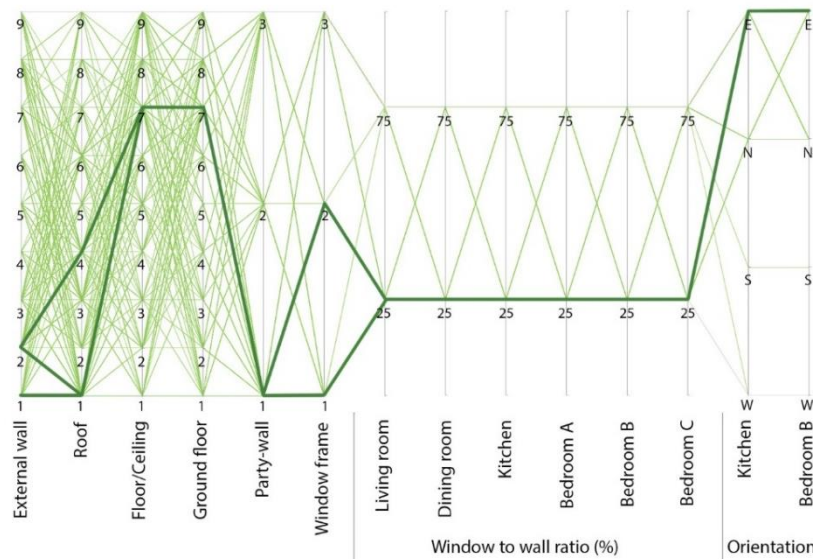


Figure 5.14: The properties of the pareto-front models of a terrace house refurbishment (for a detailed description of building components and build-ups, please refer to 5.1.3.b, and to Appendix C

B. Replacement

Figure 5.15 describes the pareto-front models of the terrace-house replacement. The figure indicates that all pareto-optimal models shared some properties: All had the same external wall, party wall and floor/ceiling build-ups, as well as window orientations (south-facing windows, whenever possible).

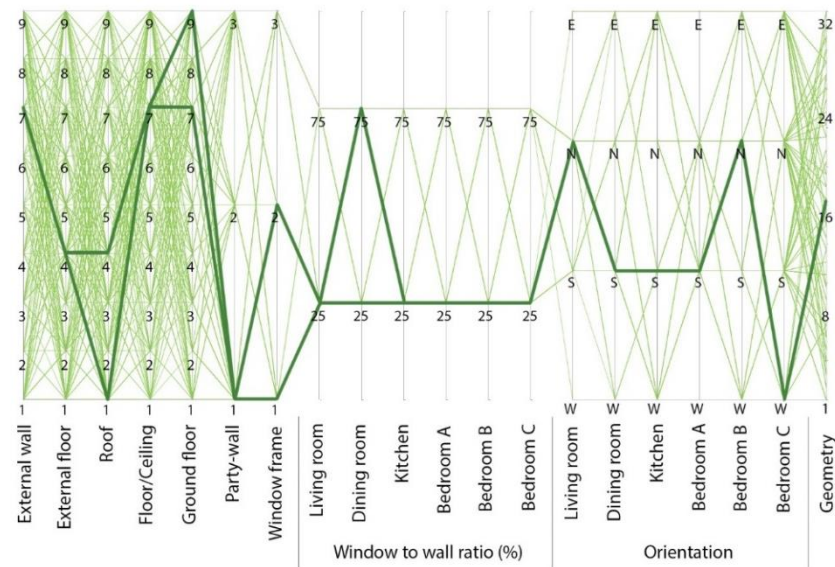


Figure 5.15: The properties of the pareto-front models of a terrace house replacement (for a detailed description of building components and build-ups, please refer to 5.1.3.b, and to Appendix D

Interestingly, all pareto-optimal models chose the same building geometry (geometry number 16, as shown in detail in Figure 5.16)– which was proven to result with the best performance, of all examined geometries. The pareto-front models differed however, in their roof, ground floor slab and windows constructions, and in the kitchen's south-facing window-to-wall ratio. It is acknowledged that the geometry that had been selected as the optimal one, in terms of LCCF and LCC, might have various shortcomings (e.g., architectural appearance, daylight distribution etc.). It is, however, pointed out that while other objectives can potentially be integrated into the optimisation process – the current framework is focused on LCCF and LCC solely.

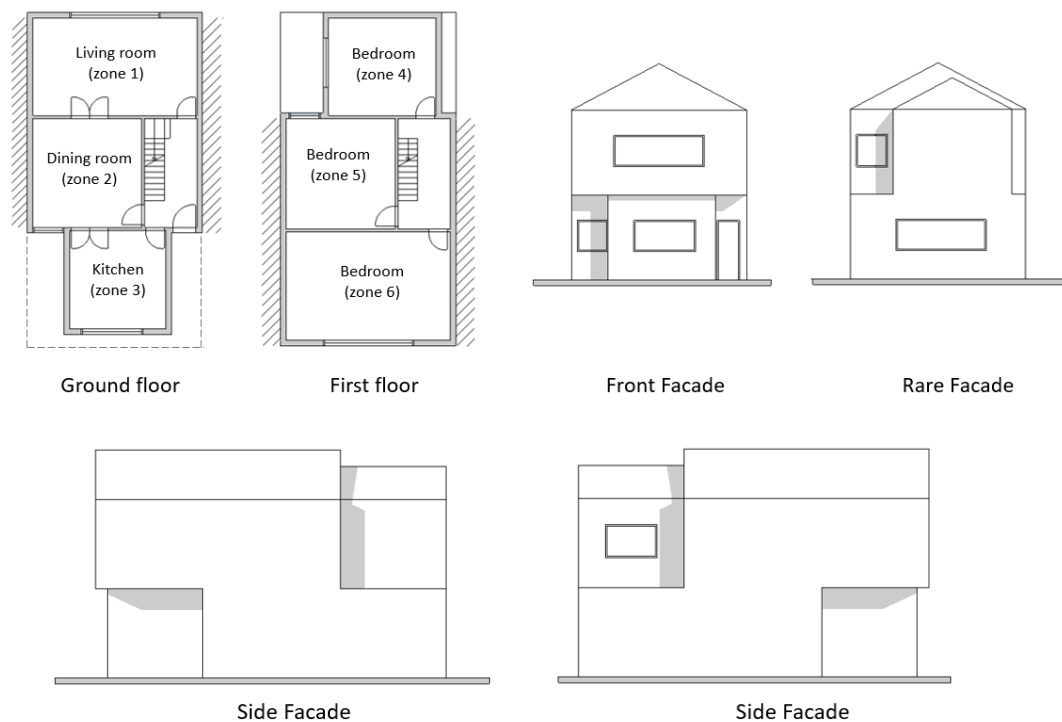


Figure 5.16: Best terrace replacement floor plans, elevations and thermal zones.

5.2.5. Aggregated Year-By-Year Overall Emissions and Costs

A year-by-year comparison between the CO₂ emissions and costs of the refurbishment and replacement scenario was carried (Figure 5.17 and 5.18), and the models with the best performance in each scenario are plotted (the 'Pareto edge' models). The performance of all other pareto-optimal models lies within the plotted lines, and their rankings, in relation to the other models, were kept unchanged throughout their lives (i.e., the best-

performing model had the best performance each year from year 0 throughout its life). It is pointed out that the models with the minimal LCCF had the largest life cycle cost and the one with the largest LCCF had minimal costs.

A. Life Cycle Carbon Footprint

Figure 5.17 shows that the refurbishment scenarios had around half the embodied CO₂ of that of the replacement scenario. This is due to the retaining of the main structure of the original building (ground floor, party walls, roof structure etc.), and the embodied CO₂ associated with the demolition of the existing building. The figure also shows, however, that while there is a significant difference in the performance of the buildings in their early stage of life, this gap is minimised later on, as the operational performance of the replacements is better than that of the refurbishment. Analysis showed that some replacement models might outperform refurbishment ones only after around 80 years.

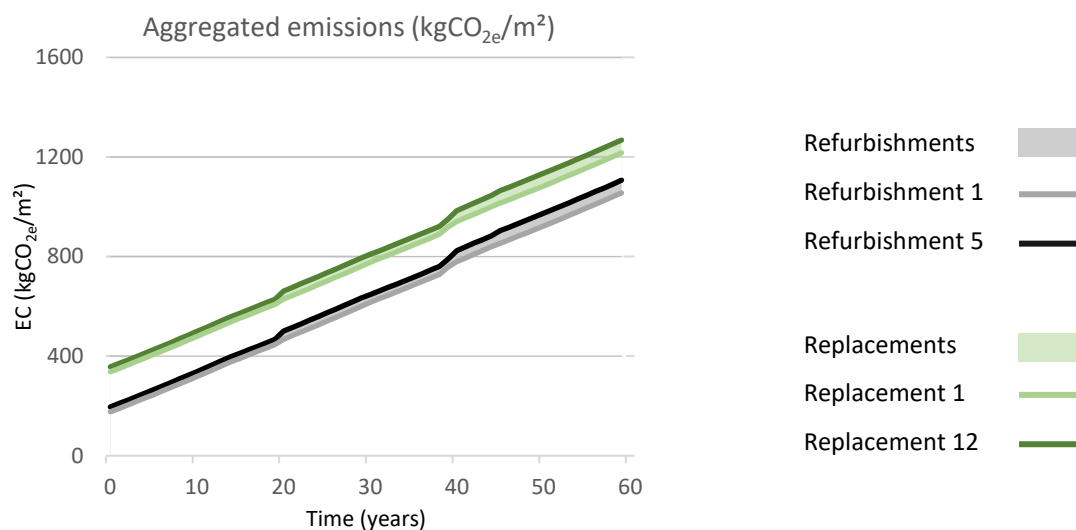


Figure 5.17: Terrace house - Aggregated annual refurbishments and replacements emissions

B. Life Cycle Cost

An aggregated year-by-year cost analysis for the optimal models (Figure 5.18) shows that the initial cost of an optimal replacement can be anything between 15-90% higher than that of the optimal refurbishment. The trend of the difference in performance is kept

throughout the analysis life. This means that it is not likely that a replacement of an existing terrace house will ever be more economical than that of its replacement.

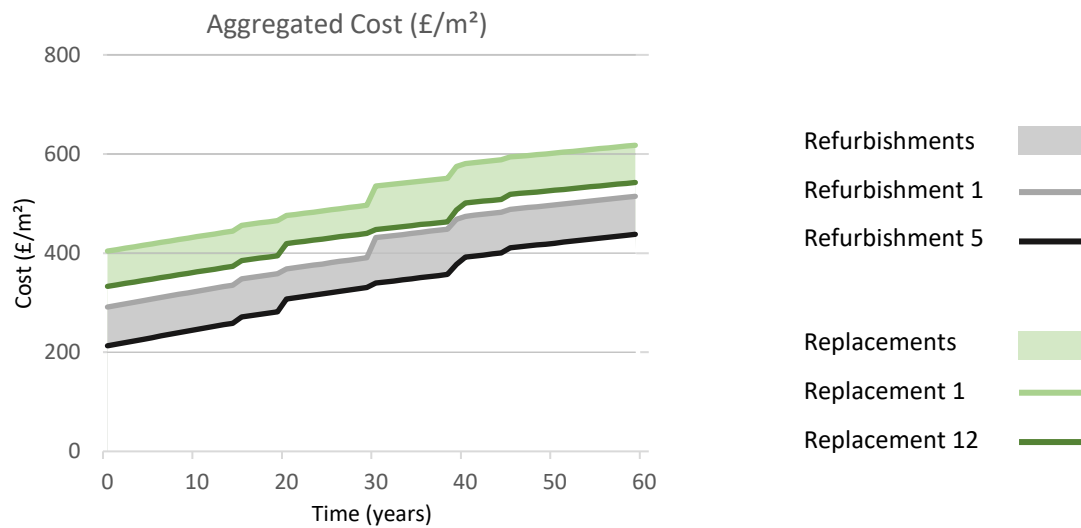


Figure 5.18: Terrace house - Aggregated annual refurbishments and replacements costs

5.2.6. Life Cycle Stages Comparison

A. Life Cycle Carbon Footprint

A comparison between the LCCF of the refurbishment and replacement best pareto edge models was carried (Figure 5.19). Results indicate that the refurbishment scenario saved around two thirds of the original building's embodied CO₂ (around 50 kgCO_{2e}/m² were taken replaced in the refurbishment, whereas around 160 kgCO_{2e}/m² were embodied in the original building). Also, results show that the replacement alternative performs better in terms of space heating emissions (B6) - around 20% lower rates - though its overall performance is still worse than that of the refurbishment.

B. Life Cycle Cost

A comparison between the refurbishment and replacements LCC (Figure 5.20) shows that for both scenarios, the initial investment (product and construction) have the highest costs throughout the optimal buildings lives. While there is a significant difference between the initial investments (A) between the two scenarios, their operational performance is similar: while the annual spending for heating and lighting (B6+B7) in the

replacement building is lower than those of the refurbishments, the savings are as little as around £11/m²/60 years (or, around £1,500 per flat over the lifetime of the building). This is associated with the high thermal performance of the refurbishment scenario, as designed to comply with the UK building regulations for refurbishments.

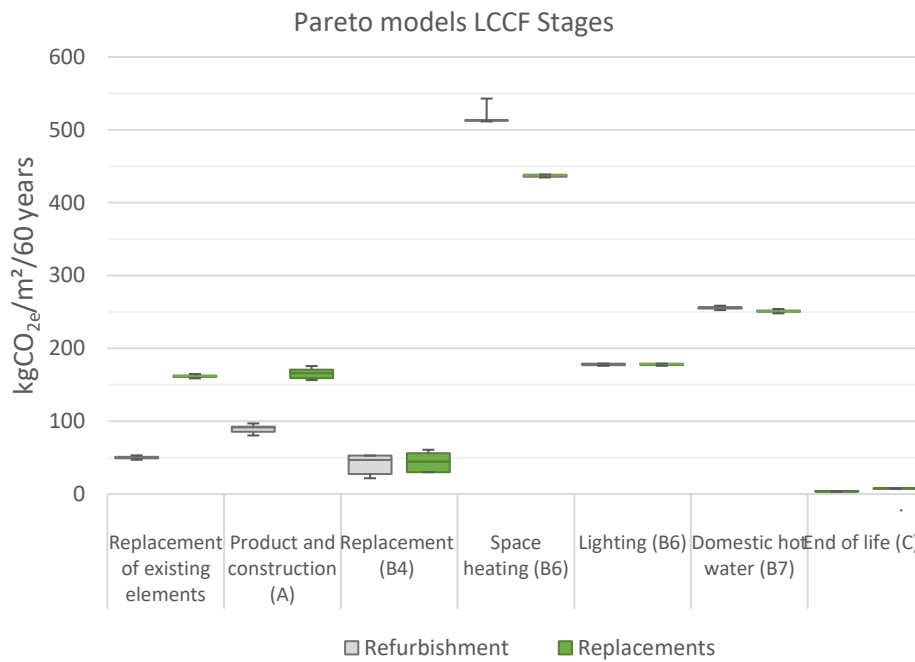


Figure 5.19: Terrace house refurbishment and replacements life cycle CO₂ stages breakdown

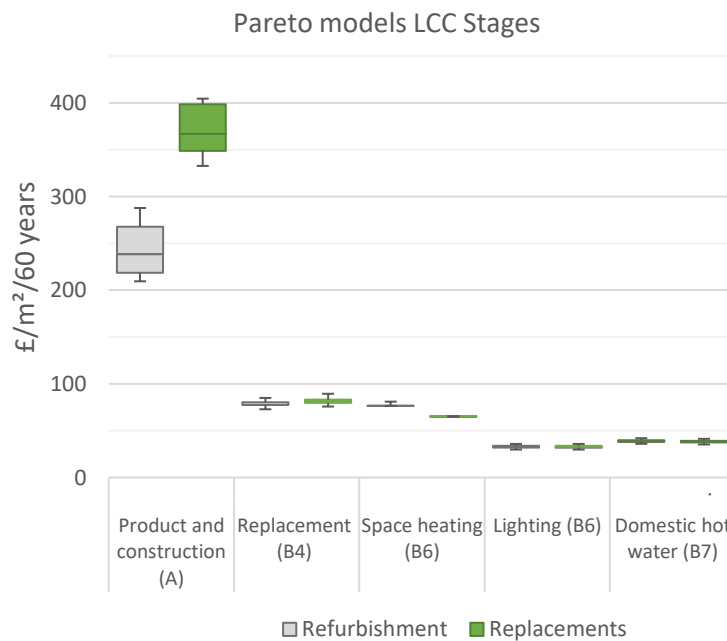


Figure 5.20: Terrace house refurbishment and replacements life cycle cost stages breakdown

C. Embodied and Operational Performance

When comparing the ratio of the embodied and operational CO₂ and cost outputs for the different scenarios, Figure 5.21 shows that the operational stage of the optimal buildings contributes most to their life cycle performance (84% for refurbishments and 70% for replacements on average, stv =2 and 1 respectively). This is well aligned with the results of the literature review, as shown in section 2.3.3. The ‘replacement of existing elements’ (i.e., the buildings materials that had been removed to enable the refurbishment or the replacement, as covered in section 5.1.5), accounts for only 4% in the case of refurbishment and for a significantly higher rate of 13% in the replacement. Unlike the LCCF analysis, the initial capital investment is the component that has the largest part of the buildings` LCC (69% for refurbishments and 77% for replacements, stv= 3 and 2 respectively). It is suggested that the different trend, when comparing the ratio of LCCF and LCC components, is due to the relatively low cost of a unit of energy (gas / electricity), whereas their emission rates are relatively high. Another reason for the opposite LCCF and LCC ratio is the different way these are calculated and in particular the skewed projection of operational costs over time following the LCC protocol calculation method, as further discussed in section 6.2.2.

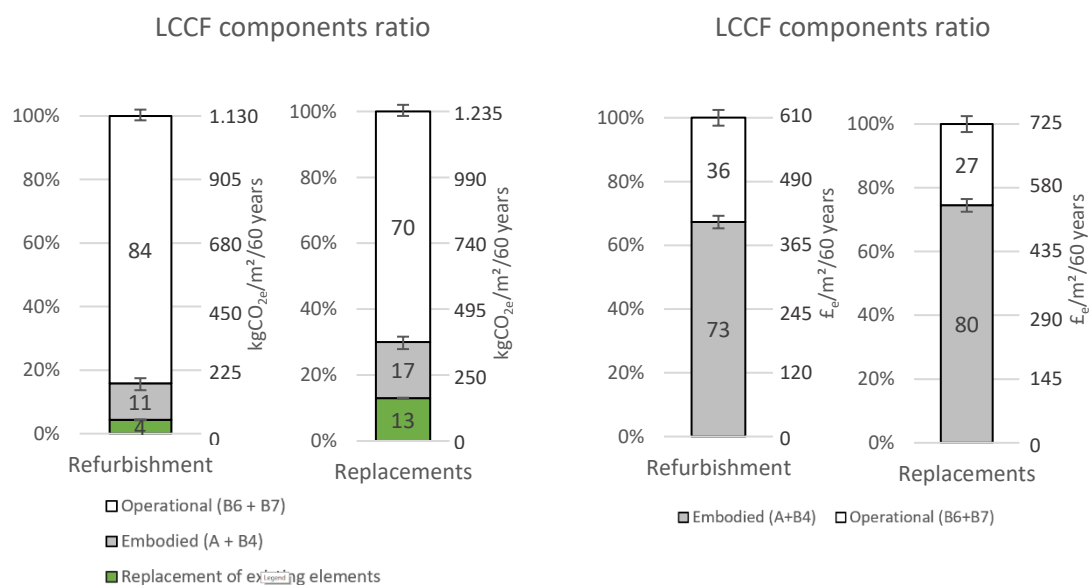


Figure 5.21: Refurbishment vs Replacement: life cycle performance breakdown

5.2.7. Embodied and Recurrent CO₂ and Cost Breakdown

Figures 5.22 and 5.23 show a breakdown analysis for the range of the embodied and recurrent CO₂ and costs (stages A and B4 in BS EN 15978:2011), for the refurbishment and replacements optimal models. The figures suggest that the ground floor slab build-up has the largest contribution for the replacement CO₂ emissions – almost three times that of the refurbishment - and it is often the most expansive element in the building. This is associated to the use of reinforced concrete for the construction of the ground floor. It is also noted that windows CO₂ and cost values vary significantly, due to their frame material – timber or uPVC.

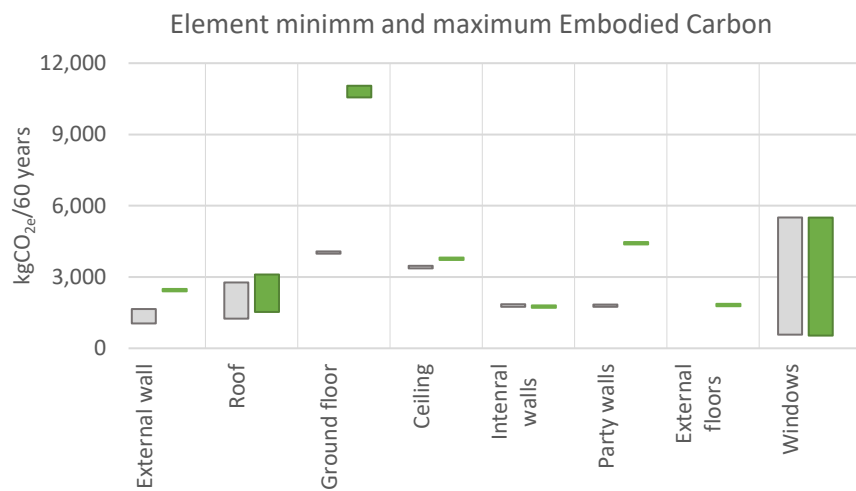


Figure 5.22: Terrace house embodied CO₂ breakdown (stages A+B4)

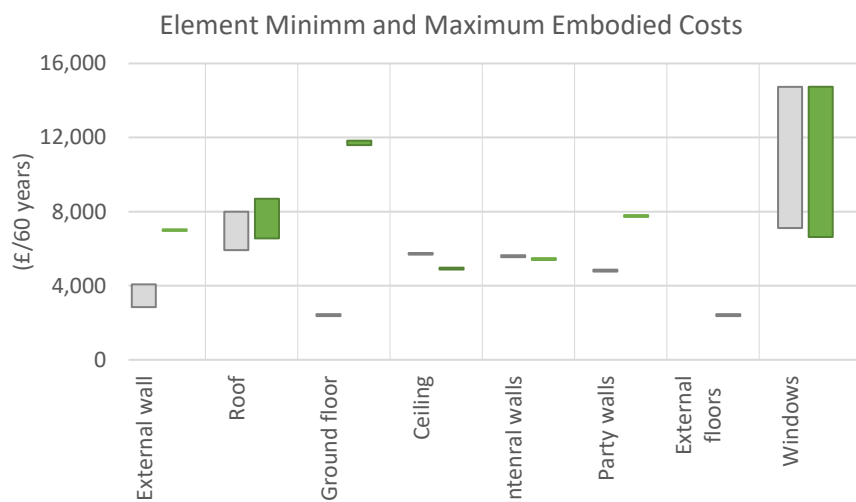


Figure 5.23: Terrace house embodied cost breakdown (stages A+B4)

5.3. Case Study 2 – Bungalow

5.3.1. The Case Study Building

The second case study examines the refurbishment and replacement of a typical London-based bungalow house. Floor plans of the house are presented in Figure 5.24 (based on Oikonomou et al., 2012). For a description of the constructions and build-ups of the existing building please refer to 5.1.3.a and Appendices C-F.

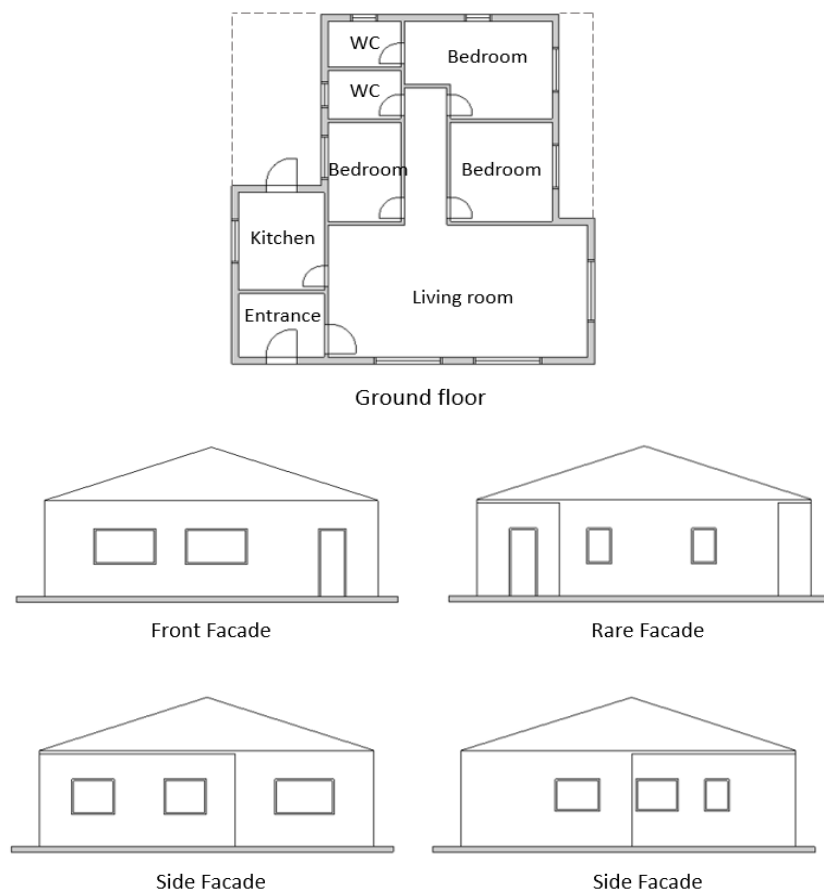


Figure 5.24: Case study 2 - A 'typical' London bungalow house (Oikonomou et al., 2012)

5.3.2. Design Scenarios

A. The Refurbishment Model

To enable thermal simulation and life cycle performance analysis, the building was divided. The thermal zones for the bungalow are shown in Figure 5.25. Potential window orientations are identified and marked on the relevant external walls.

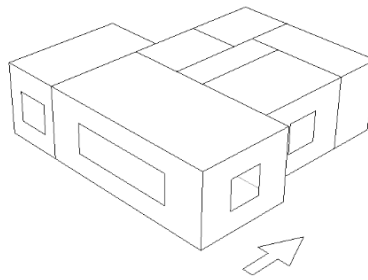


Figure 5.25: Case study 2 – Thermal zones and potential windows orientation for the optimisation of the bungalow refurbishment

B. The Replacement Models

For the life cycle impact assessment of replacement buildings, PLOOTO was used for the generating various floor layouts and spatial arrangements. Table 5.6 shows a detailed description of the possible room sizes ranges, as well as their possible proximities to other rooms. These were based on features of the original bungalow house, so that the new geometries will be of similar floor area, volume and use. PLOOTO was stopped once it reached 50 different designs (Figure 5.26), as new designs showed greater similarities.

Thermal Zone		Width		Length		Adjacent to room
		Minimum	Maximum	Minimum	Maximum	
Ground floor	1 Living room	400	600	400	700	6, 5
	2 Bedroom 1	300	450	300	450	6
	3 Bedroom 2	300	450	300	450	6
	4 Bedroom 3	300	450	300	450	6
	5 Kitchen	250	400	300	400	1
	6 Hall + toilets	100	800	100	800	1, 2, 3, 4

Table 5.6: Case study 2 - PLOOTO inputs – possible room sizes and proximity matrix

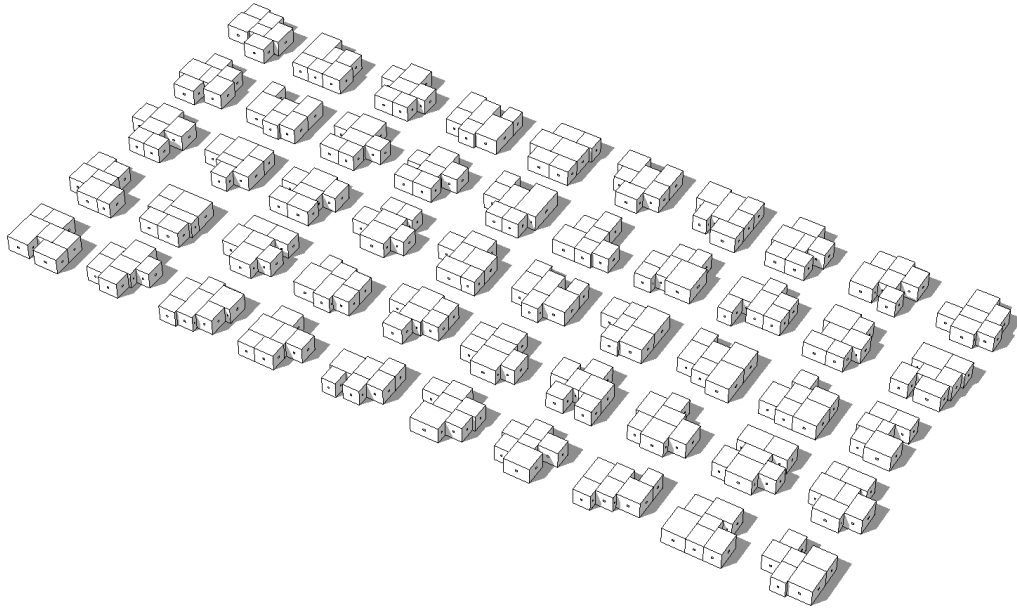


Figure 5.26: PLOOTO outputs – the 50 new-build bungalow designs

5.3.3. Optimisation Results and Pareto Fronts

As described in section 5.1.1, three optimisation runs were carried out and analysed for each design scenario, for verification purposes. The next case studies analysis, however, displays only the analysis of a single optimisation run, as all three runs had the same results.

A. Refurbishment

Figure 5.27 shows the output of the optimisation of a bungalow refurbishment. Results show that a clear pareto front was found, and that the system converged in around 15-17 generations. 14 pareto-optimal models were found. Their LCCF values ranged between 1,340 – 1,500 kgCO_{2e}/m² and their LCC ranged between 550 – 680 £/m² - aligned with the literature results (section 2.3.3).

B. Replacement

Figure 5.28 shows the replacement optimisation outputs. All three runs reached similar search space and an identical set of pareto front, with 14 pareto front models. The optimisation process converged after around 12 - 14 generations. The LCCF range for the

optimal replacements was between 1,750-1,850 kgCO_{2e}/m², and their LCC ranged between 750-890 £/m² - aligned with the literature results (section 2.3.3).

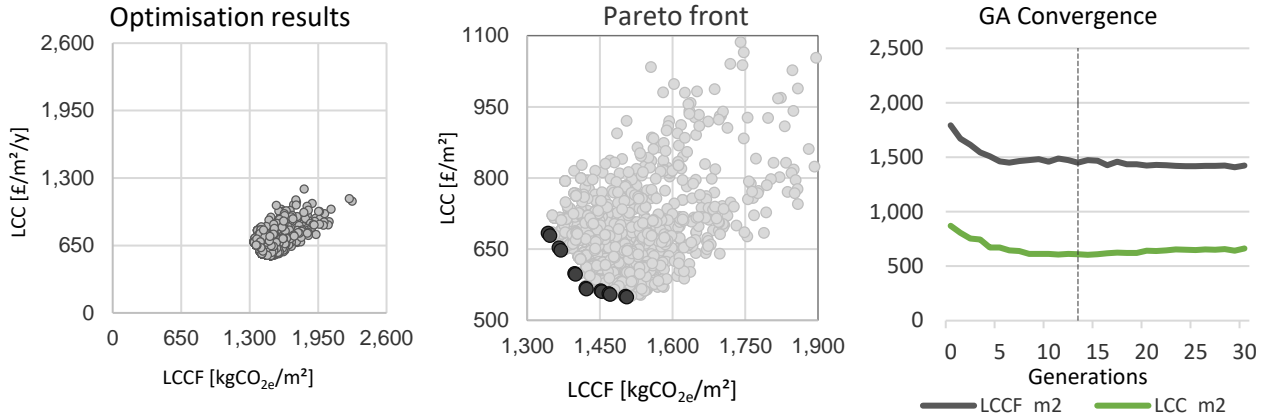


Figure 5.27: Bungalow refurbishment results – LCCF/LCC for 60 years, pareto front and GA convergence

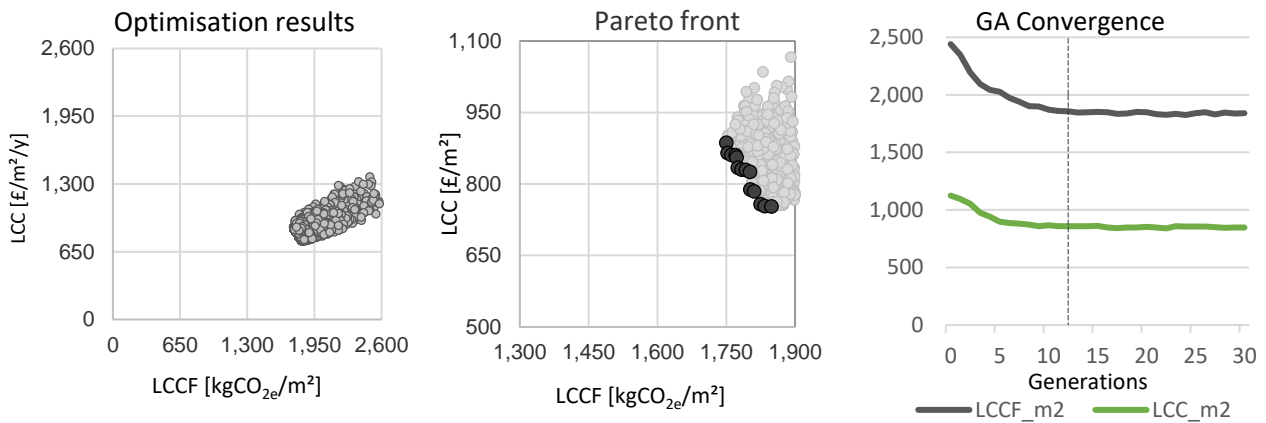


Figure 5.28: Bungalow replacement results – LCCF/LCC for 60 years, pareto front and GA convergence

C. Pareto-Fronts Comparison

A comparison between the pareto models of the bungalow refurbishment and replacement scenarios (Figure 5.29) shows that under the assumptions and scope of this case study, the refurbishment scenario is found to be favourable. An average optimal refurbishment performs around 20% better in terms of LCCF and around 30% better, in terms of LCC, than an average optimal replacement for the assumed 60 years (average refurbishment and replacement LCCF values: 1,423 and 1,792 kgCO_{2e}/m² respectively).

Average refurbishment and replacement LCC values: 595 and 820 £/m² respectively, n1=14, n2=14, P<0.05 for both averages).

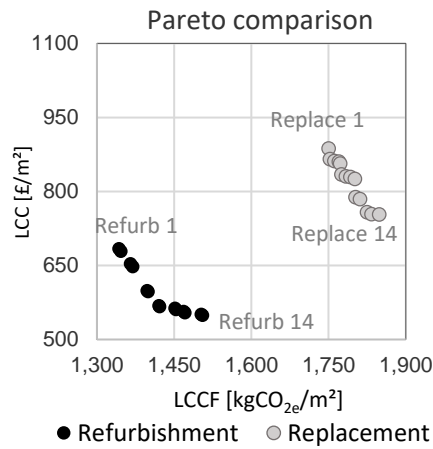


Figure 5.29: Refurbishment vs Replacement: Pareto models comparison

5.3.4. Pareto Models Analysis

A. Refurbishment

An examination of the pareto-front models (Figure 5.30) shows that all pareto-front models resulted with the same ground floor refurbishment means, minimal WWR (25%) and had south facing window orientation whenever this was possible (two of the bedrooms had only one possible window orientation).

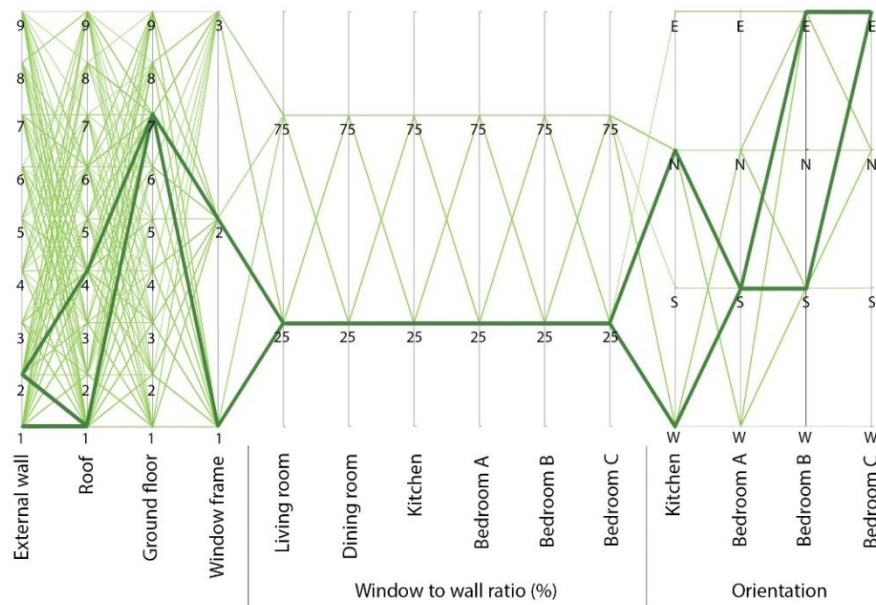


Figure 5.30: The properties of the pareto-front models of a bungalow house refurbishment (for a detailed description of building components and build-ups, please refer to 5.1.3.b, and to Appendix C

The pareto models differed their external walls and roofs build-ups, as well as with their window frames and their non-south-facing window orientations.

B. Replacement

The bungalow replacement pareto front was consistent of fourteen models Figure (5.31). All models had shared some properties: All models had the same external wall build-up, almost all models had minimal WWR - 25% (except one bedroom) and south-facing windows – whenever this was possible. All pareto-optimal models had geometry number 44 as their spatial arrangement (Figure 5.32), which, coupled with the other building properties, proved to result with the best performance among all other spatial arrangements.

The roof and ground floor build-ups, however, as well as the window frame materials, were different across the pareto-front models.

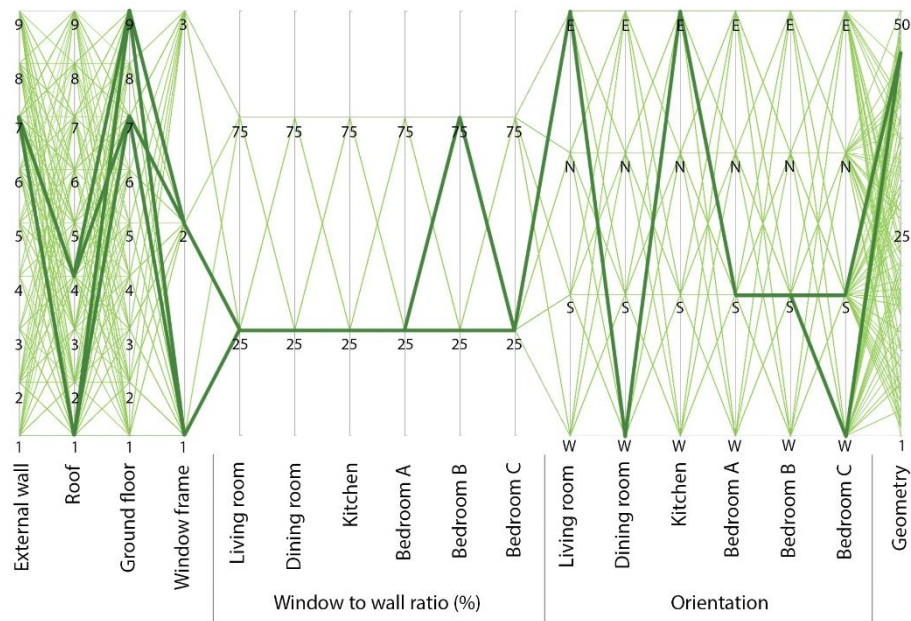


Figure 5.31: The properties of the pareto-front models of a bungalow house replacement (for a detailed description of building components and build-ups, please refer to 5.1.3.b, and to Appendix D

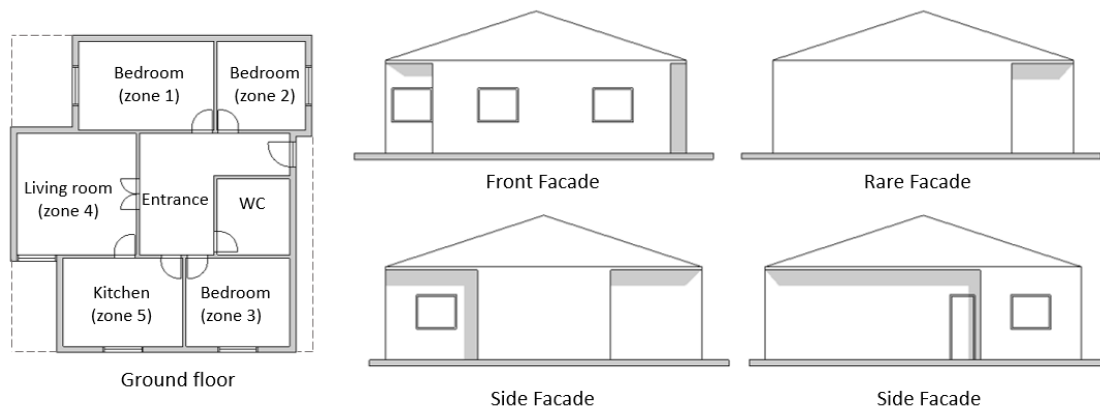


Figure 5.32: Best bungalow replacement floor plan, elevations and thermal zones.

5.3.5. Aggregated Year-By-Year Overall Emissions and Costs

Emissions and costs year-by-year analysis was carried out for all pareto-front models, and the models with the best LCCF and LCC (the 'Pareto edge' models) in each scenario were plotted (Figures 5.33 and 5.34). A close examination has found that the performance of all other pareto-optimal models lays within the plotted lines throughout the assumed building life span.

A. Life Cycle Carbon Footprint

Figure 5.33 shows that the embodied CO₂ in the replacement scenarios is more than double that double than that of the refurbishments. Also, while there is a small difference between the embodied CO₂ within each scenario (emissions at year 0) - the buildings performance differs as a function of time, and end ups with around 10% difference. This is an indication that the buildings thermal performance is different.

Lastly, figure 5.33 also suggests that the refurbishment scenarios are consistently better than the replacements, and that there is no apparent case in which a replacement might outperform a refurbishment (this might happen only after more than 250 years).

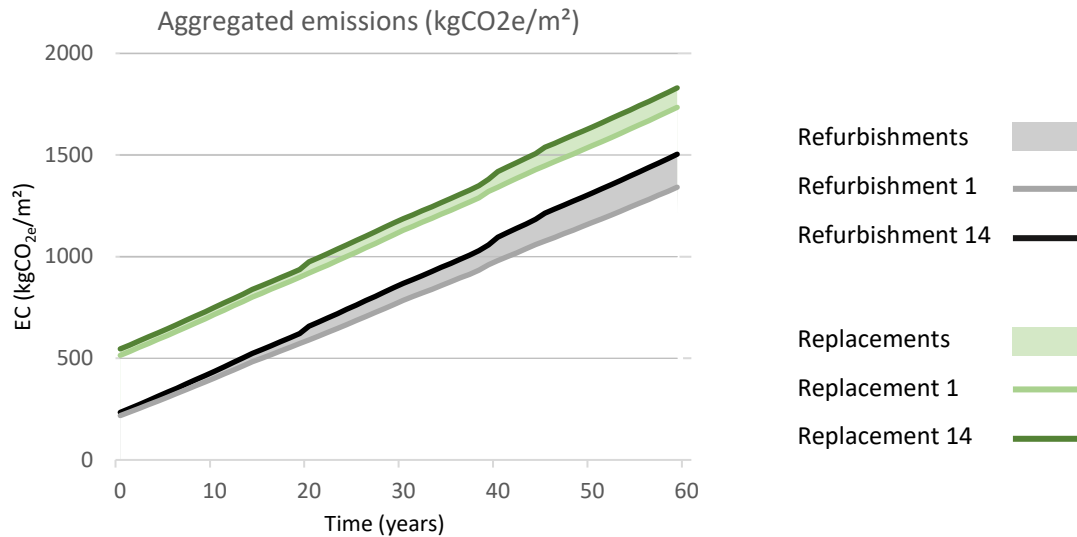


Figure 5.33: Bungalow - Aggregated annual refurbishments and replacements emissions

B. Life Cycle Cost

An aggregated year-by-year cost analysis for the optimal models (Figure 5.34) shows that the initial cost of an optimal replacement can be as little as 5% higher than an optimal refurbishment, but some replacements can cost more than double than a refurbishment. Furthermore, 32 to 38 years down the life of the project, the performance of certain refurbishment scenarios is only marginally better than that of the best replacement. The difference in performance, however, widens later on, due to the replacement and refurbishments profiles of the buildings.

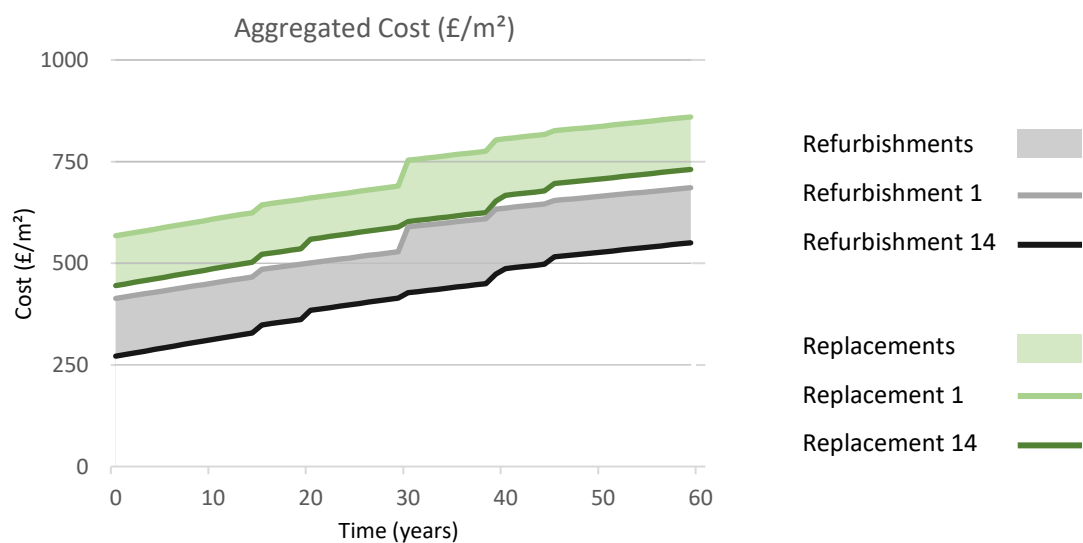


Figure 5.34: Bungalow - Aggregated annual refurbishments and replacements costs

5.3.6. Life Cycle Breakdown Comparison

A. Life Cycle Carbon Footprint

A comparison between the LCCF of the refurbishment and replacement pareto edge models (Figure 5.35) shows that the refurbishment scenario had saved around 75% of the original building's embodied CO₂ (only 80 out of the original building's 270 kgCO₂e/m² had been taken out during demolition works). Also, results show that the great majority of the replacement buildings performed better in terms of operational CO₂ (B6), while their whole life cycle performance was still worse than those of the refurbishments.

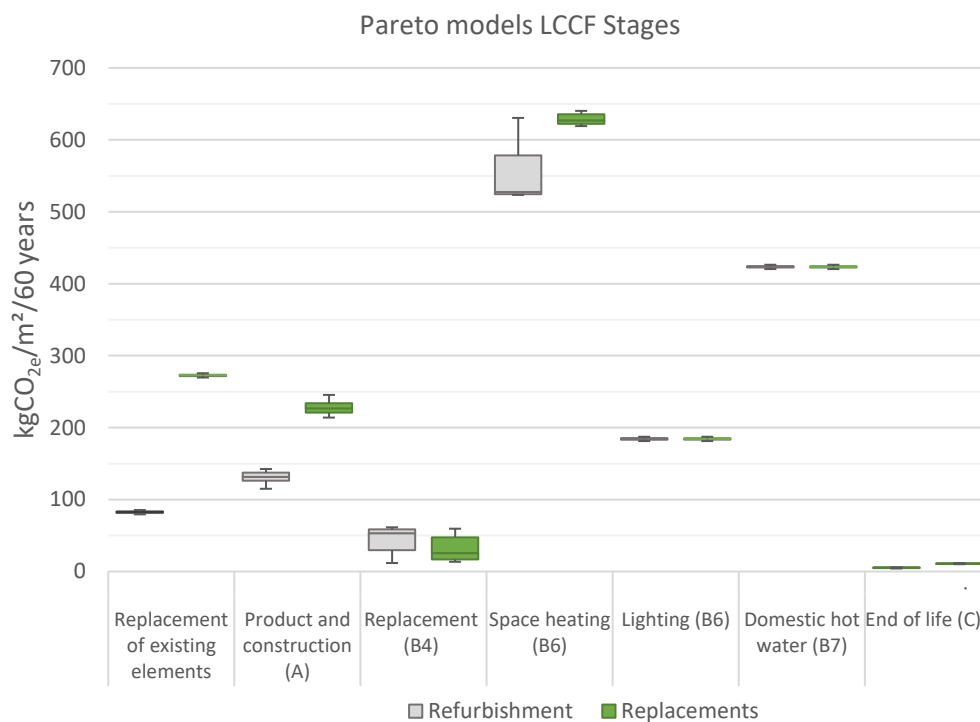


Figure 5.35: Bungalow refurbishment and replacements life cycle CO₂ stages breakdown

B. Life Cycle Cost

A comparison between the life cycle cost of the refurbishment and replacement pareto edge models (Figure 5.36) shows that the main contributor to the buildings life cycle cost is the initial investment (A). Furthermore, the overall cost of replacements throughout the buildings lives (B4) is within a similar range of the overall spending for space heating.

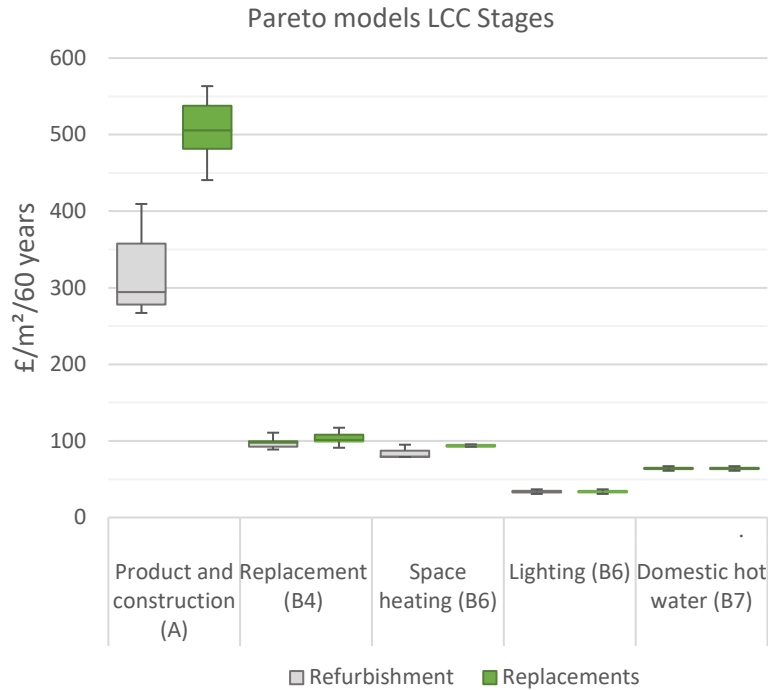


Figure 5.36: Terrace house refurbishment and replacements life cycle cost stages breakdown

C. Embodied and Operational Performance

Finally, when comparing the ratio of the embodied and operational CO₂ and cost outputs for the different scenarios, Figure 5.37 shows that the buildings' operational stage contributes more in the case of the refurbishment scenario than in the replacement (79%, stv=2m compared with 67%, stv = 1 for the replacement). This is well aligned with the results of the literature review, as shown in section 2.3.3. However, it is the initial capital investment, that contributes most to the buildings LCC (74%, stv=3 for refurbishment and 80, stv =2 for replacement). It is suggested that the reason for this opposite trend is due to the relatively low costs of energy, compared with its emission rates, as well as due to the skewed projection of operational costs over time, as further discussed in section 6.2.2.

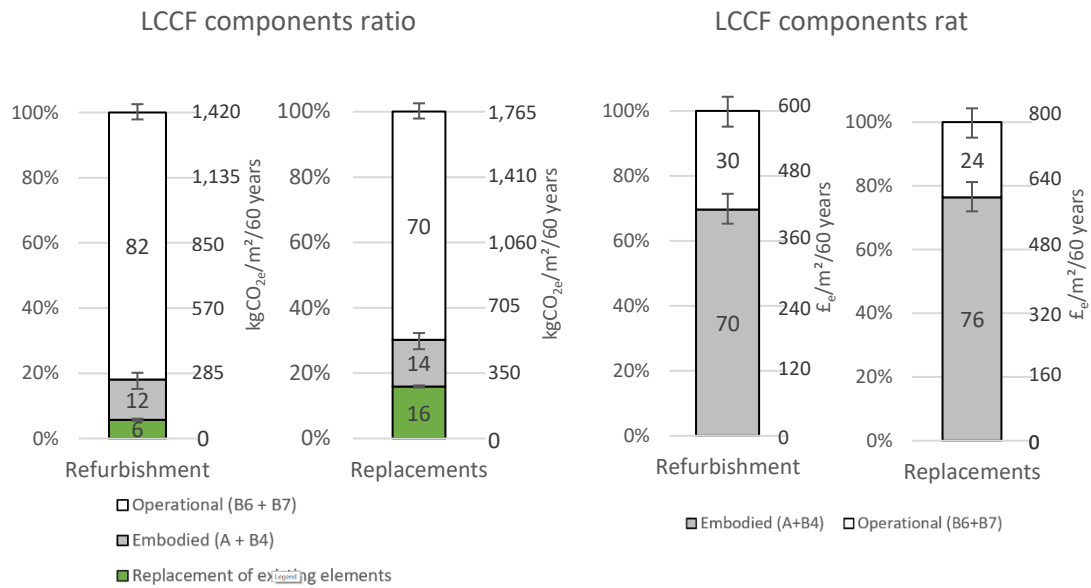


Figure 5.37: Refurbishment vs Replacement: life cycle performance breakdown

5.3.7. Embodied and Recurrent CO₂ and Cost Breakdown

A breakdown of the embodied and recurrent CO₂ and costs ranges (stages A and B4 in BS EN 15978:2011) is presented in Figures 5.38 and 5.39, for the pareto-optimal models of the two design scenarios. Results show that the embodied and recurrent CO₂ emissions and costs of most building elements in the replacement scenario are larger than those of the refurbishment scenario (since some construction elements are retained in the refurbishments). This is particularly evident in the case of the ground floor slab: which has around four times higher embodied CO₂ and cost values than the refurbishment. This is associated to the use of concrete and reinforcements related to the construction of a new ground floor slab and the building foundations. The embodied emissions and costs of the external walls are quite similar when comparing the two scenarios. This is because the UK regulations, the U-Value of refurbished external walls is achieved by designing similar build-ups to those of replacements.

Lastly, it is noted that there is a great variability in both the embodied CO₂ and cost of the windows. This is because of the optimal buildings had one of two extreme cases of window frames – either timber (low CO₂ but very expensive) or uPVC (high in CO₂ but more affordable).

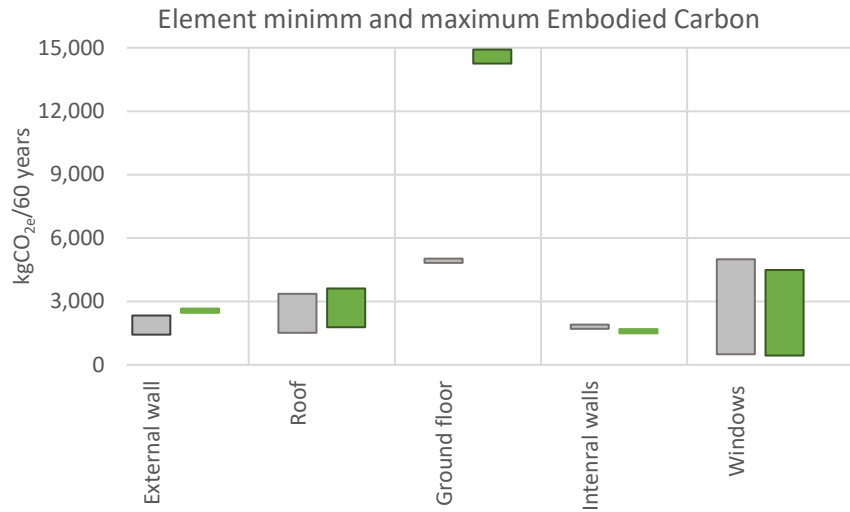


Figure 5.38: Bungalow embodied CO₂ breakdown (stages A+B4)

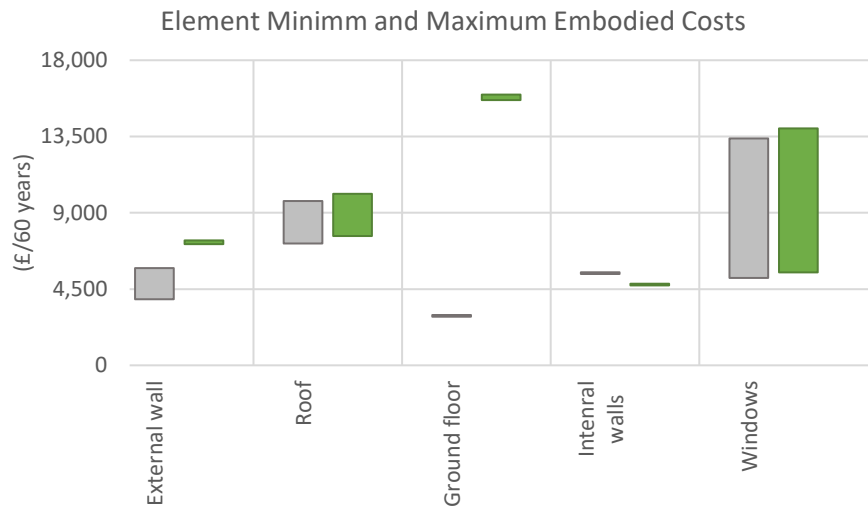


Figure 5.39: Bungalow embodied cost breakdown (stages A+B4)

5.4. Case Study 3 – Block of Flats

5.4.1. The Case Study Building

The third case study examines the refurbishment and replacement of a typical London-based block of flats. Drawings of the examined building are presented in Figure 5.40 (based on Oikonomou et al., 2012). For a description of the existing building construction and build-ups, please refer to 5.1.3.a and Appendices C – F.

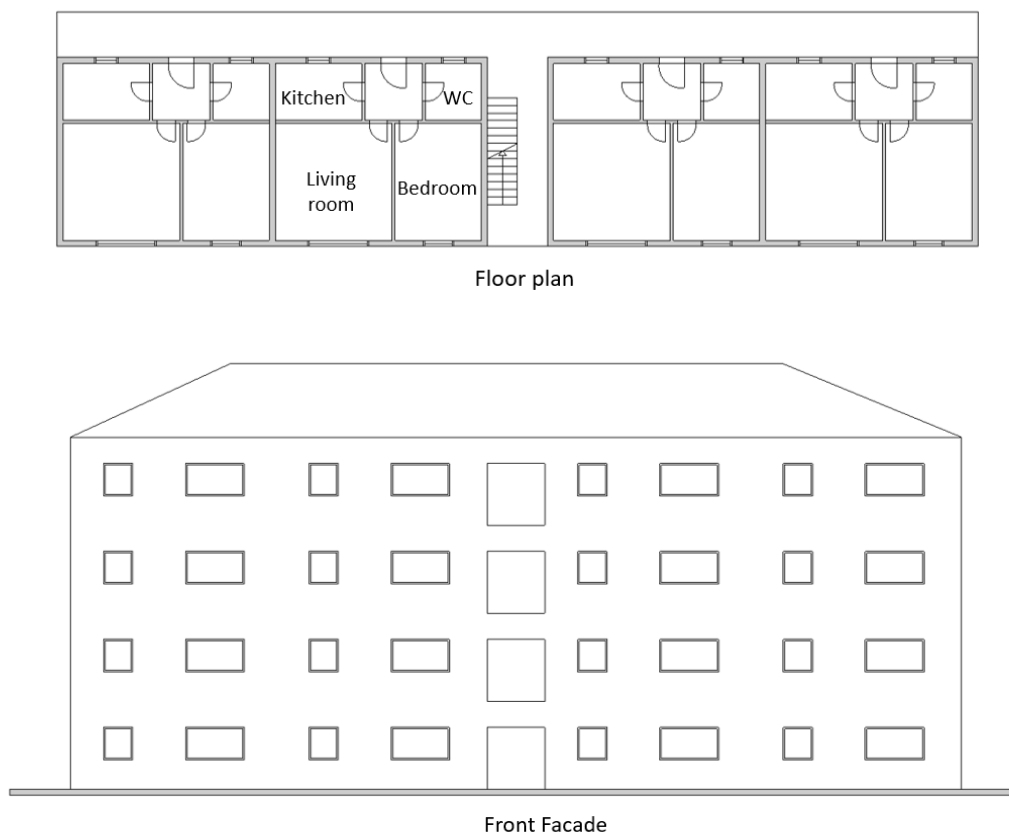


Figure 5.40 Case study 3 - A 'typical' London block of flats (Oikonomou et al., 2012)

5.4.2. Design Scenarios

A. The Refurbishment Model

For the thermal simulation analysis, the building was divided into thermal zones as shown in Figure 5.41. For simplification purposes, the thermal simulation included the modelling of a single storey with adiabatic roof and floor. The energy demand of this single storey was then multiplied by the number of floors, to get the overall energy demand of the entire building. While it is noted that this approach might miss-represent the actual thermal

performance of the ground and top floors, it still gives a very good approximation of the thermal performance of the entire building. As for the embodied CO₂ and cost calculations – these did include the actual constructions of the ground floor slab and roof, and were therefore not affected by the simplified modelling approach.

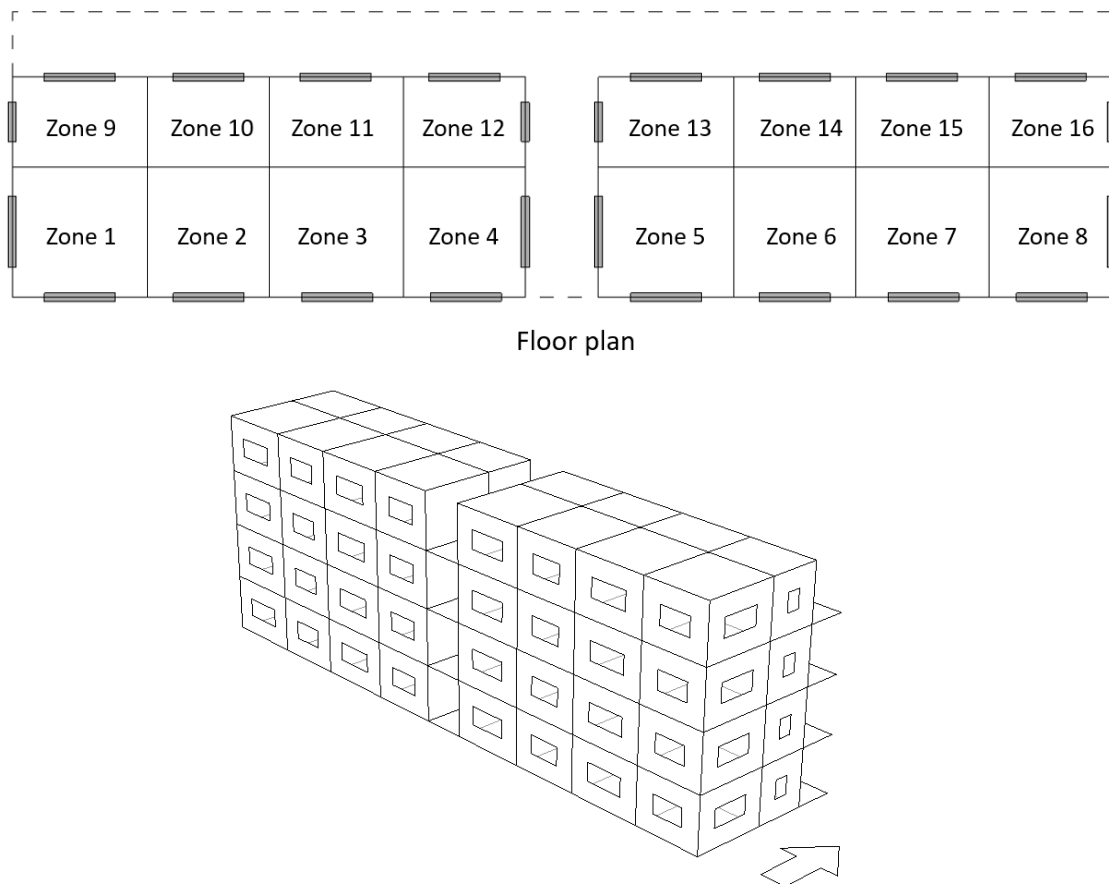


Figure 5.41 Case study 2 – Thermal zones and potential windows orientation for the optimisation of the block of flats refurbishment

B. The Replacement Models

For the life cycle impact assessment of replacement buildings, PLOOTO was used for the generation of floor layouts and spatial arrangements. As explained in section 5.1.5, to examine a more realistic replacement scenario in which an existing block of flats might be demolished and rebuilt in higher density, the replacement buildings had five storeys, 2.5m high each (compared to four storeys, 3m high in the refurbishment scenario).

As the original typology of a block of flats is not in use in contemporary affordable housing schemes, it was decided to use PLOOTO for the generation of a more contemporary and realistic five storey “Point-block” – a building with a vertical core at its centre.

Table 5.7 shows a detailed description of the possible room sizes ranges, as well as their possible proximities to other rooms. To examine contemporary design scenarios, the kitchen and living rooms are designed as one space (an opened kitchen). Furthermore, for modelling simplification purposes, flat entrances and toilets were combined with the communal vertical core (stairs and lift), as they share similar occupancy and use patterns. PLOOTO was stopped once it reached 27 different designs (Figure 5.42), as new designs showed greater similarities.

Thermal Zone	Width		Length		Adjacent to room
	Minimum	Maximum	Minimum	Maximum	
1 Vertical core	500	1200	500	1200	2,4,6,8
2 Living room + Kitchen A	400	700	400	700	1,3
3 Bedroom A	350	500	350	500	2
4 Living room + Kitchen B	400	700	400	700	1,5
5 Bedroom B	350	500	350	500	4
6 Living room + Kitchen C	400	700	400	700	1,7
7 Bedroom C	350	500	350	500	6
8 Living room + Kitchen D	400	700	400	700	1,9
9 Bedroom D	350	500	350	500	8

Table 5.7: Case study 3 - PLOOTO inputs – possible room sizes and proximity matrix

As in the case of the refurbishment modelling and simulation, the thermal model included a single story with adiabatic ceilings and floors. The energy demand outputs were later multiplied by the number of storeys. The energy demand of this single story was then multiplied by the number of floors to get the overall energy demand of the entire building. The embodied CO₂ and costs calculations did include the actual constructions of the ground floor slab and roof and were therefore not affected by the modelling approach.

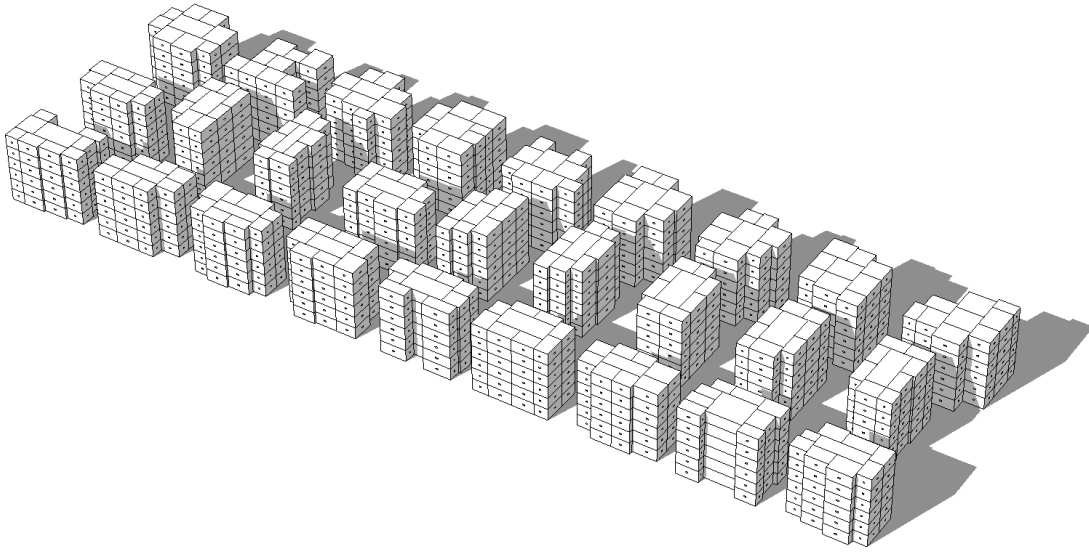


Figure 5.42: PLOOTO outputs – the 27 new-build designs

5.4.3. Optimisation Results and Pareto Fronts

As described in 5.1.1, for verification purposes, 3 optimisation runs were carried out and analysed. Since the outcome of all three runs was similar, only the results of a single optimisation run is presented for each design scenario.

A. Refurbishment

Figure 5.43. Results show the output of the optimisation of the refurbishment of the existing block of flats. The optimisation results show a clear pareto-optimal front (22 models), and a convergence after 8 – 10 generations. The LCCF and LCC range of the pareto-optimal buildings was between 1,200-1,300 kgCO_{2e}/m² and 500 – 660 £/m² respectively - aligned with the literature results (section 2.3.3).

B. Replacement

Figure 5.44 shows the replacement optimisation outputs. Results show that a pareto-optimal front of 12 models was found, at a convergence around the 15th generation. The pareto optimal models had LCCF in the range of between 1,325 – 1,360 kgCO_{2e}/m² and LCC of between 580– 630 £/m² – in alignment with the literature results (section 2.3.3).

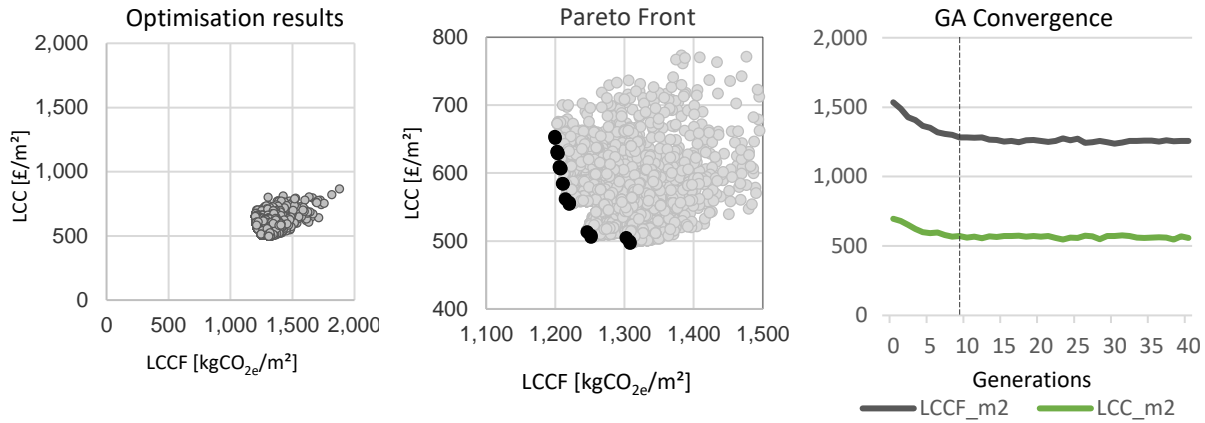


Figure 5.43: Block of flats refurbishment results – LCCF/LCC for 60 years, pareto front and GA convergence

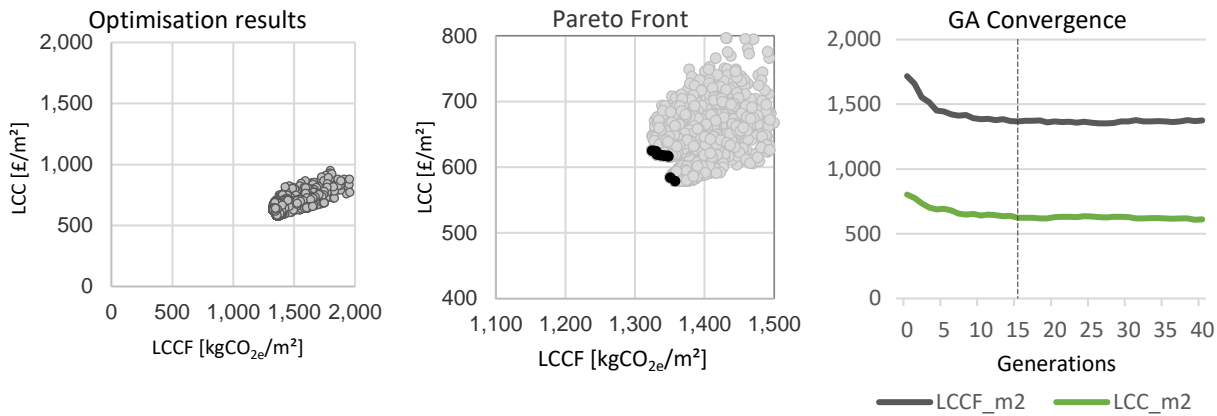


Figure 5.44: Block of flats replacement results – LCCF/LCC for 60 years, pareto front and GA convergence

C. Pareto-Fronts Comparison

A comparison between the pareto models of the block of flats refurbishment and replacement scenarios (Figure 5.45) shows that under the assumptions and scope of this case study, the refurbishment of a block of flats is found to be favourable: An average optimal refurbishment performs around 10% better in terms of LCCF, and around 6% better in terms of LCC, than a typical optimal replacement for the assumed 60 years (average refurbishment and replacement LCCF values: 1,227 and 1,340 kgCO_{2e}/m² respectively. Average refurbishment and replacement LCC values: 579 and 613 £/m² respectively, n1=22, n2=12, P<0.05 for both averages).

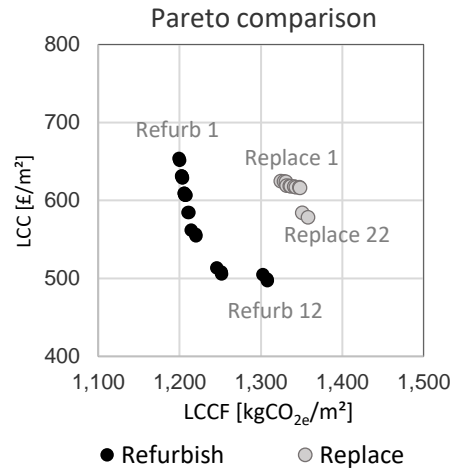


Figure 5.45: Refurbishment vs Replacement: Pareto models comparison

5.4.4. Pareto Models Analysis

A. Refurbishment

An examination of the pareto-front models (Table 5.46) shows that all pareto-optimal models resulted with the same floor/ceiling build-ups minimal WWR and had southern window orientation. The pareto models differed with their external walls constructions, roof and ground floor and build-ups and with their window frame materials. Furthermore, while the WWR of the bedrooms and kitchens in all optimal models were 25%, their living rooms WWR could either be 25 or 75%.

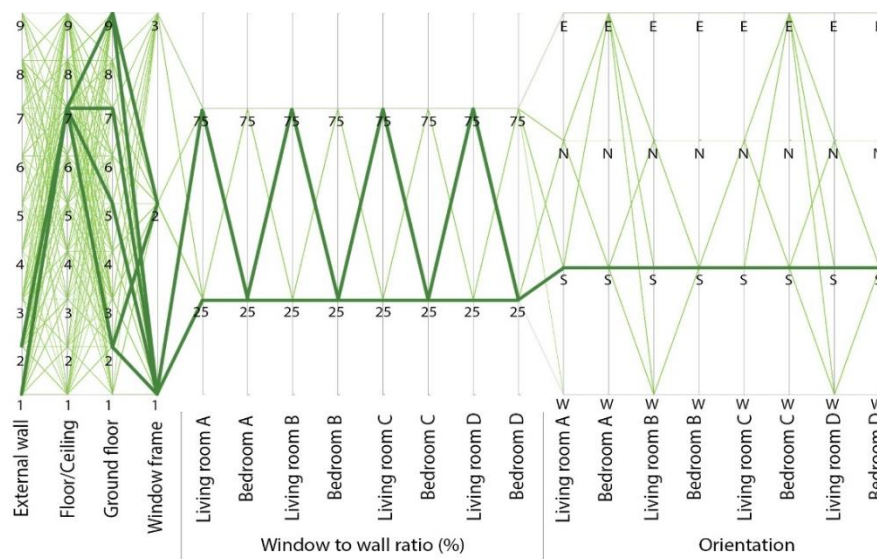


Figure 5.46: The properties of the pareto-front models of a block of flats refurbishment (for a detailed description of building components and build-ups, please refer to 5.1.3.b, and to Appendix C

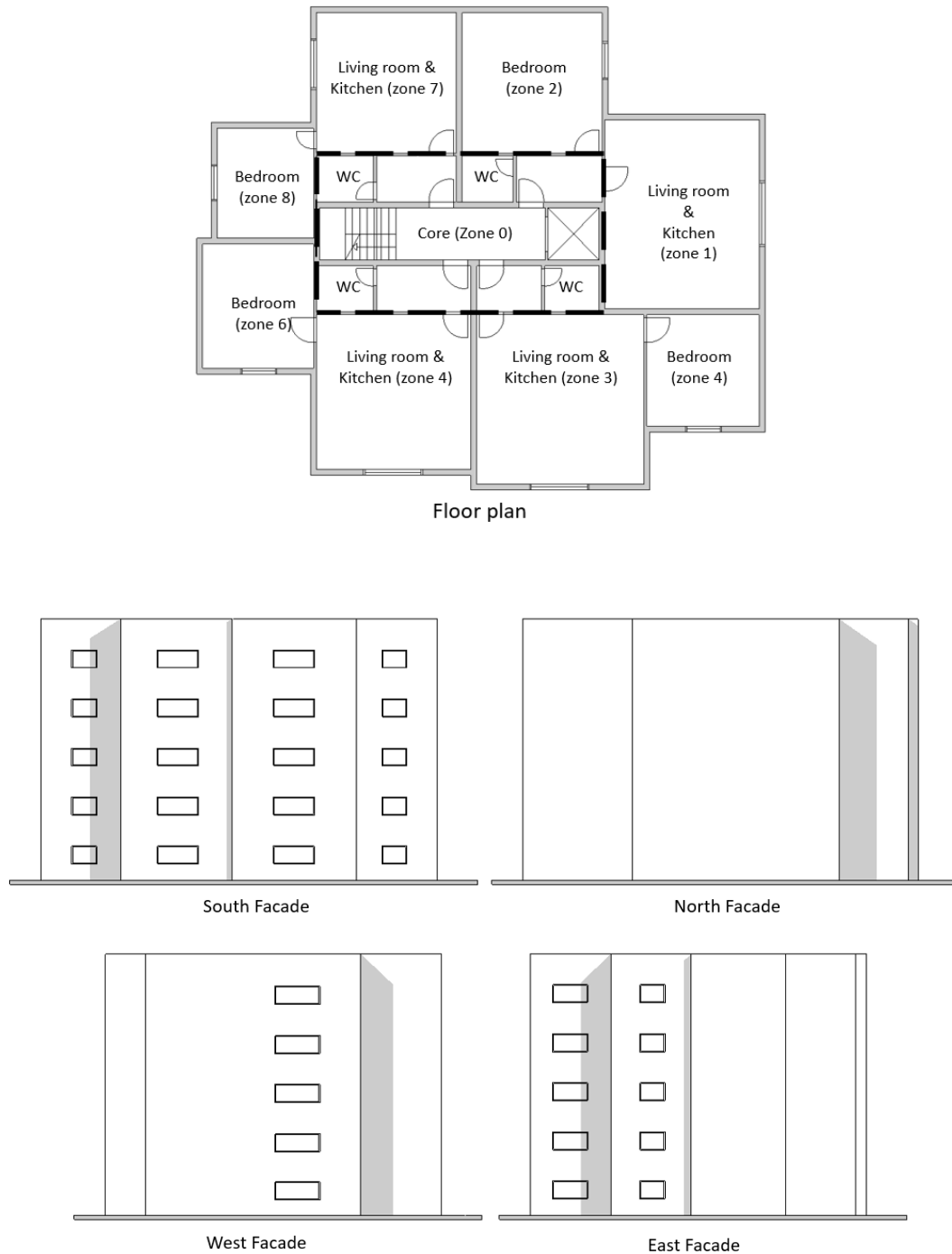


Figure 5.48: Best flats replacement floor plan, elevations and thermal zones.

5.4.5. Aggregated Year-By-Year Overall Emissions and Costs

Aggregated year-by-year emissions and costs analysis was carried for all pareto-front models, and the models with the best LCCF and LCC (the 'Pareto edge' models) in each scenario were plotted (Figures 5.49 and 5.50). A close examination has found that the

performance of all other pareto-optimal models lays within the plotted lines throughout the assumed building life span.

A. Life Cycle Carbon Footprint

Figure 5.49 shows that the embodied CO₂ of the replacement scenarios was more than double than that of the refurbishment ones (around 470 kgCO_{2e}/m² compared with around 200 kgCO_{2e}/m²). While the performance of the replacement scenario is still better by the time the buildings reach their assumed life span, some replacement buildings can perform better than refurbishments after around 65 years, as their operation and maintenance seem to more CO₂ efficient.

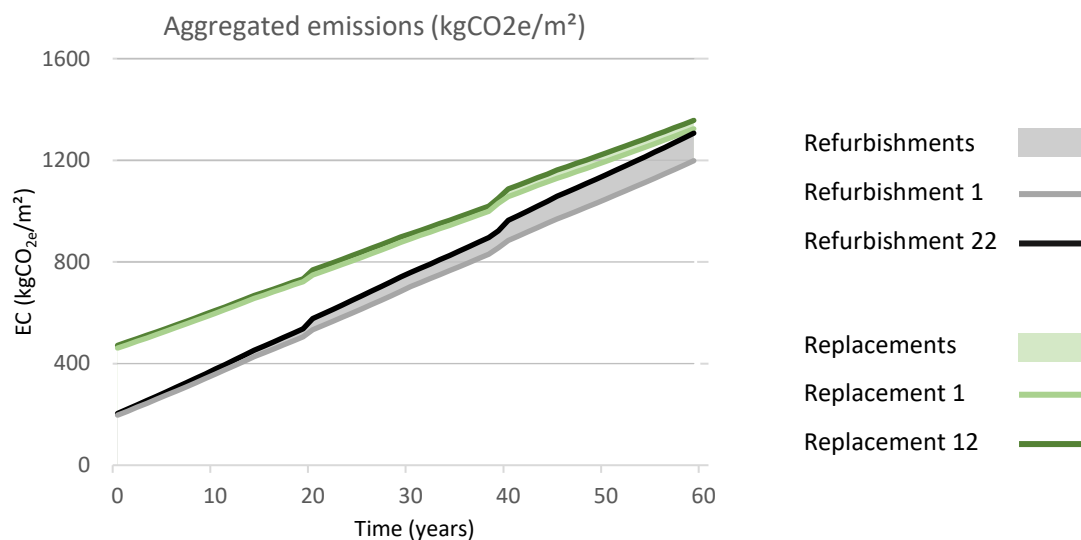


Figure 5.49: Block-of-flats - Aggregated annual refurbishments and replacements emissions

B. Life Cycle Cost

And aggregated year-by-year cost analysis (Figure 5.50) shows that there is no clear pattern in terms of annual cost efficiency. Refurbishments can be either the most expansive or more affordable alternatives. Interestingly, some refurbishments (e.g., refurbishment 1 in Figure 5.50) started with a lower initial investment then some replacements (e.g., replacement 12), but performed worse after 30 years, due to better operational performance and periodic refurbishment and maintenance actions. This

indicates that the cost comparison between the two design scenarios is case-study dependent.

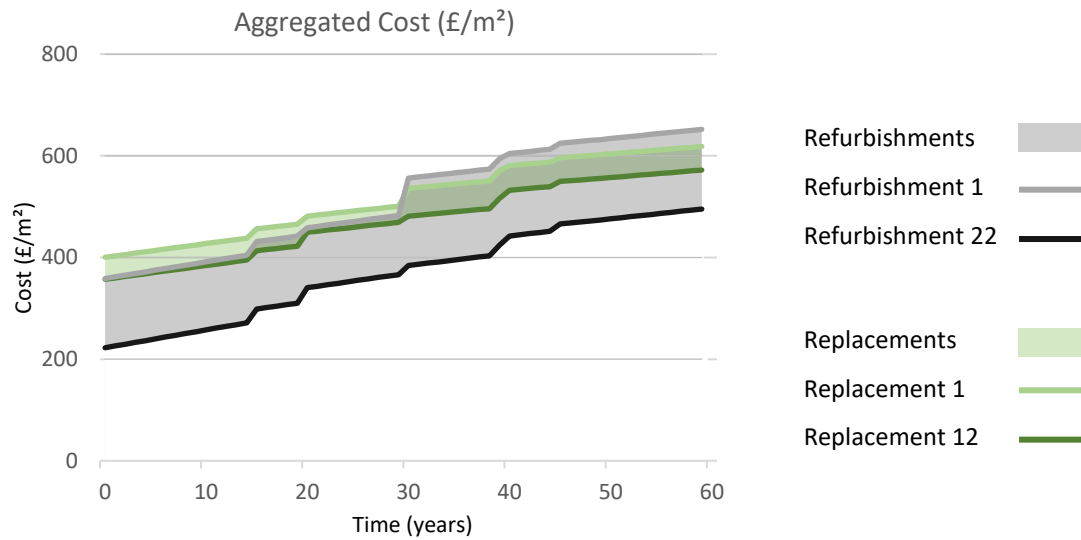


Figure 5.50: Block-of-flats - Aggregated annual refurbishments and replacements costs

5.4.6. Life Cycle Breakdown Comparison

A. Life Cycle Carbon Footprint

A life cycle stages comparison between the refurbishment and replacement pareto edge models (Figure 5.51) shows that the refurbishment scenario had saved around 60% of the original building's embodied CO₂ (only 100 of the original building's 350 kgCO₂e/m² were taken out during demolition works). The product and construction phase (A) of the replacement was around double than the refurbishments, and that all replacement buildings were more energy efficient (B6) than the refurbishment ones.

B. Life Cycle Cost

A life cycle cost breakdown comparison between the refurbishment and replacement scenarios (Figure 5.52) shows that the initial capital costs (A) of replacements are higher than refurbishments, while the costs of repairs and replacements (B4) are lower. Overall life energy costs (B6) are similar in both scenarios.

It is also pointed that while the annual spending for heating and lighting (B6+B7) in the replacement building is lower than those of the refurbishments, the savings are fairly low – only around £13/m²/60 years (or, around £700 per flat over the lifetime of the building).

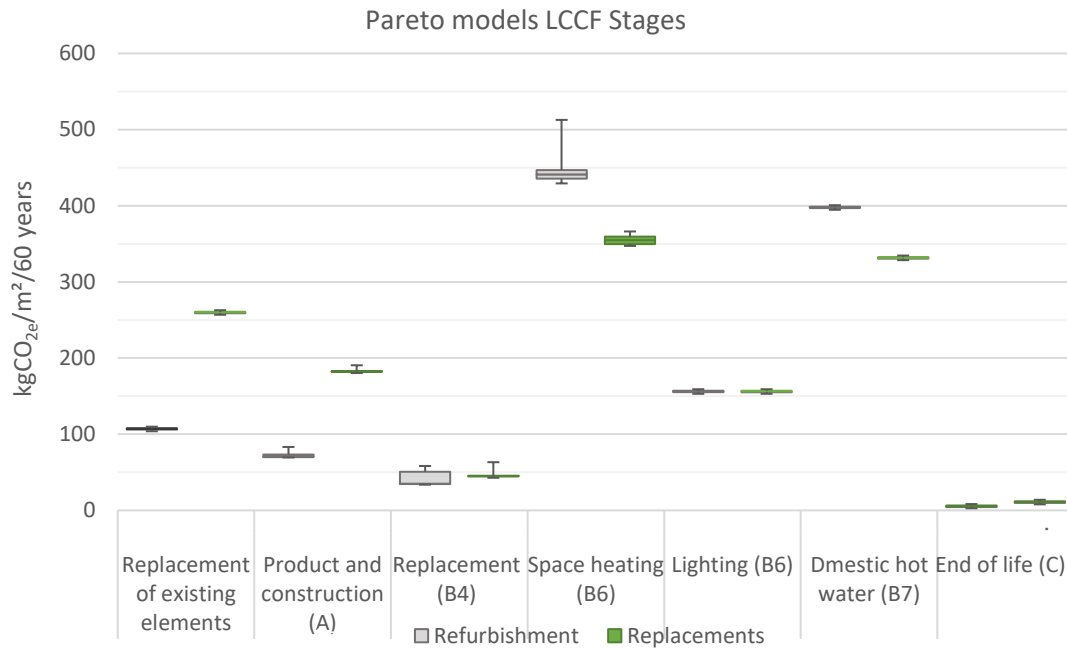


Figure 5.51: Block-of-flats refurbishment and replacements life cycle CO₂ stages breakdown

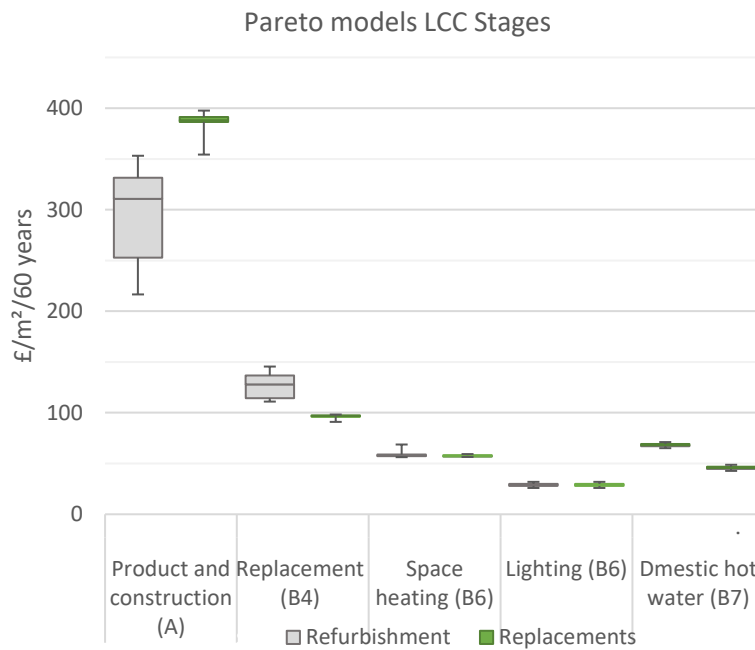


Figure 5.52: Block-of-flats refurbishment and replacements life cycle cost stages breakdown

C. Embodied and Operational Performance

In comparing the ratio of embodied and operational performance of both scenarios, Figure 5.53 shows that there is a big difference in the contribution of the operational-related CO₂ of the two scenarios (82%, stv = 1 for the refurbishment and 63%, stv = 1 for the replacement). As in previous case studies, while operational energy consumption contributes most to the buildings' CO₂ emissions, it is their initial capital investment that contributes most to their cost. It is suggested that this is both because the cost of a unit of energy is relatively low whereas its emission rates are relatively high, and due to the skewed projection of operational costs over time, as further discussed in section 6.2.2.

The 'replacement of existing elements' (i.e., the materials that had been removed to enable the refurbishment or the replacement to take place, as covered in section 5.1.5), accounts for only 9% in the case of refurbishment and for nearly a fifth of that of a replacement – which becomes a significant contributor to the LCCF of the replacement.

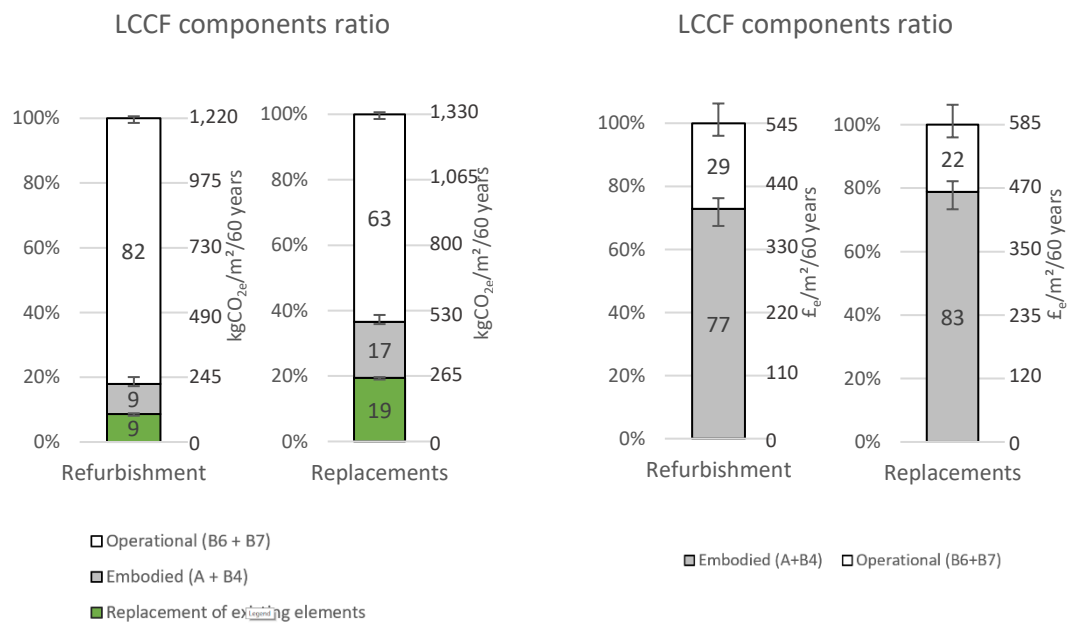


Figure 5.53: Refurbishment vs Replacement: life cycle performance breakdown

Embodied and Recurrent CO₂ and Cost Breakdown

A breakdown of the embodied and recurrent CO₂ and costs ranges (stages A and B4 in BS EN 15978:2011) is presented in Figures 5.54 and 5.55, for the pareto-optimal models of

the two design scenarios. Results show that the embodied and recurrent CO₂ and costs most building components in the replacement scenarios are larger than those of the replacements. This is expected, as in the refurbishment scenario, some elements (mainly those related to construction) are retained, whereas in the case of a replacement – new construction had to be built. This is particularly evident in the case of the ground floor slab and internal floor slabs: The ground floor build-up included the reinforced concrete slab – a CO₂ intensive building element – which was retained in the case of the refurbishment. As for the floor/ceiling slabs – the replacement scenario had one storey more than the refurbished building (4 versus 5 storeys), which also contributed to the embodied CO₂ of the replacements floor/ceiling windows and internal and external walls. It is noted that the great variability in the windows CO₂ and cost is because the optimal buildings had one of two extreme choices for their window frames - either timber frame (low CO₂ but very costly) or uPVC (high in emissions but more affordable).

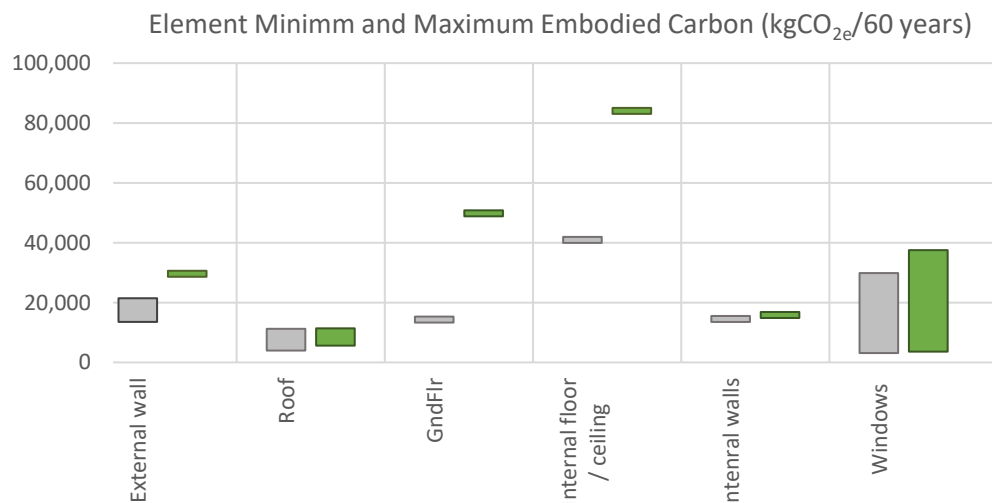


Figure 5.54: Block-of-flats embodied CO₂ breakdown (stages A+B4)

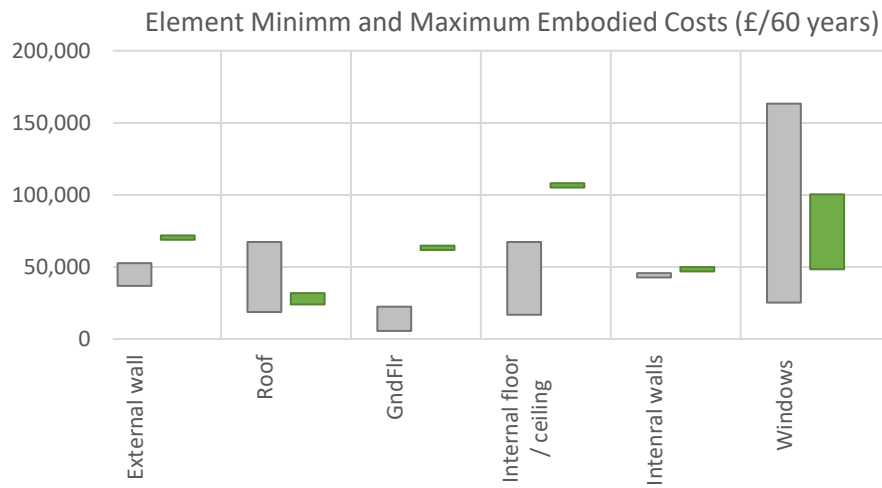


Figure 5.55: Block-of-flats embodied cost breakdown (stages A+B4)

6. Discussion

This chapter sets out a discussion regarding the findings of the case study analysis from Chapter 5. This is carried out in relation to the research objectives, literature review and other contextual topics. The discussion revolves around the following four concepts: A) The implementation of the computational framework, B) Life cycle analysis protocols, C) A summary of the analysis of the case study buildings, and D) Future developments in the optimisation of buildings for life cycle performance.

6.1. The Implementation of the Computational Framework

This section discusses points related to the proposed computational framework and its implementation.

6.1.1. Operational Use Optimisation vs. Life Cycle Performance Optimisation

While operational energy consumption (consumption at the use stage) is widely used as the main proxy for evaluating building performance in current compliance schemes, benchmarking and research studies, the proposed computational framework adopted the 'life cycle performance' as its performance metric due to its holistic approach.

To better understand the impact the selected metric has on study results and decision making in the context of refurbishment and replacements (processes that are influenced by both embodied and operational performance), this section sets out to compare the results of the two optimisation procedures:

A. Original metric: The first is an optimisation in which the objectives are the reduction of the more commonly-used annual energy consumption and costs ($\text{kWh/m}^2/\text{year}$ and $\text{£/m}^2/\text{year}$ for electricity and space and water heating).

B. The proposed framework: The second is an optimisation in which the objectives are improving the life cycle performance efficiencies, namely: LCCF ($\text{kgCO}_{2e}/\text{m}^2/60 \text{ years}$) and LCC ($\text{£/m}^2/60 \text{ years}$), as covered in section 5.1.

As this section aims to explore potential discrepancy between the results of two optimisations settings rather than carrying an investigation of the nature of the discrepancy, a single case study (that of a terrace house replacement) was used.

Figure 6.1 shows that the pareto-optimal solutions for the two optimisation runs are different: While a clear pareto front was achieved in the case of the LCCF/LCC optimisation, a single optimal model was found in the annual energy consumption / annual energy costs optimisation. Also, the searched space in that case was linear – due to the linear relationship between energy use and overall energy costs.

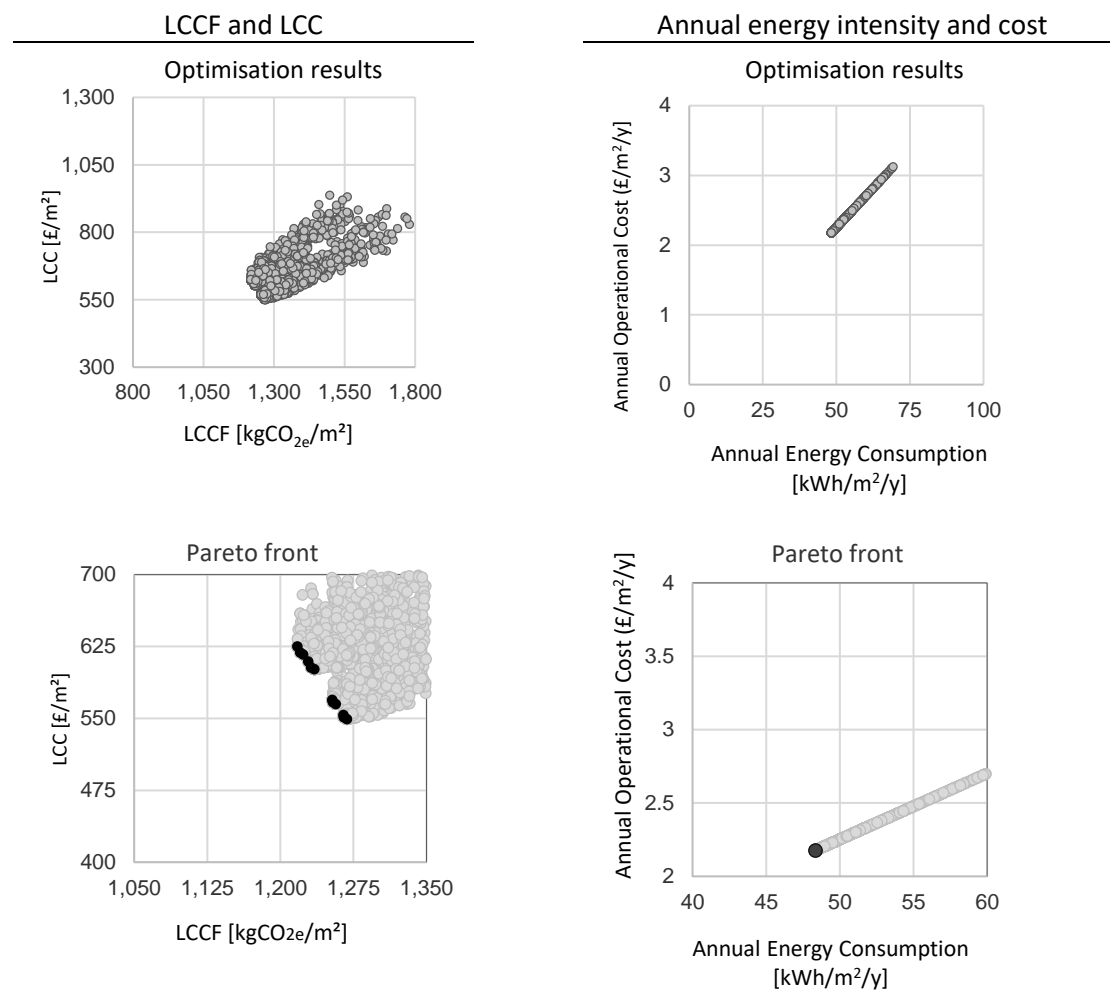


Figure 6.1: Terrace house optimisation results and pareto front comparison: LCCF/LCC (left), annual energy intensity/annual energy cost (right).

An examination of the optimal models in the two optimisation scenarios revealed that while both optimisation runs had found that geometry number 16 (Figure 5.16) was the optimal one (when having minimal window-to-wall-ratio), the optimal models did not show any similarities in terms of build-ups. The ‘annual energy performance’ optimisation had simply used all the building materials and components that had minimal U-Value (highly insulated build-ups), while the ‘life-cycle performance’ optimisation had found other materials – presumably those that had the best balance between minimal U-value, replacement rates, affordability and emissions-efficiency during production.

To further understand the impact performance criteria on decision making and study results, the LCCF and LCC values of the optimal ‘annual energy performance’ model were plotted against the pareto-optimal LCCF/LCC models. Figure 6.2 shows that this model had achieved 1,387 kgCO_{2e}/m² and 668 £/m², compared to an average 1,244 kgCO_{2e}/m² and 586 £/m² of the pareto-optimal models. This shows that optimising buildings design to minimise annual energy use resulted with around 12% higher LCCF and nearly 15% higher LCC, (more than a total of £11,000, discounted over 60 years, or £16,500 undiscounts), compared to the actual LCCF/LCC optimal design.

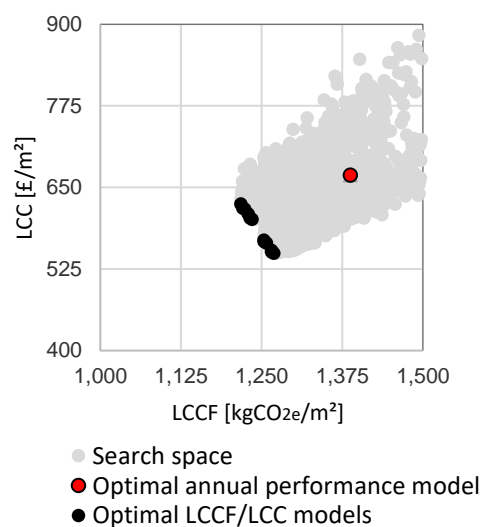


Figure 6.2: The LCCF and LCC performance of the optimal annual performance model, against the LCCF/LCC pareto front and optimisation search space

Recommendation A: As the UK government had committed to reduce CO₂ emissions in the built environment (rather than energy consumption), it is recommended to promote the investigation of the more comprehensive approach of 'performance' in buildings: exploring the contribution of the emissions that are incurred during the construction and maintenance of buildings, throughout their lives, rather than focusing on their annual energy performance solely.

6.1.2. Refurbish or Replace? - Operational vs. Life-Cycle Performance Optimisations

Following the conclusion of section 6.1.1, a further investigation was carried to explore the potential impact of using different metrics, on the decision-making process, when searching for the favourable design alternative in terms of refurbishment or replacement. The aim of this analysis was to examine whether the comparison between refurbishment and replacements, using the different metrics, will result in similar conclusions. The optimisations were carried for all building types, using the following proxies:

A. Original metric: energy consumption and costs (kWh/m²/year, £/m²/year for electricity and space and water heating).

B. The proposed framework: LCCF and LCC (kgCO_{2e}/m²/60 years, £/m²/60 years).

Figure 6.3. shows the performance of the pareto-optimal models of all case studies and scenarios, expressed in energy intensity (kWh/m²/year) and LCCF (kgCO_{2e}/m²/60 years).

For the Bungalow case study, optimisation results showed that the refurbishment option was favourable for both performance metrics. However, for the terrace house and for the block of flats case studies, the optimisation results showed contradictory trends: while from the perspective of annual energy intensity (kWh/m²/y) the replacement scenario was found to be favourable, it was the refurbished scenario that achieved better



Figure 6.3: Terrace house, bungalow and block-of-flats energy intensity (kWh/m²/y) and LCCF (kgCO₂e/m²/60 years) as performance evaluation metrics.

performance in terms of LCCF (kgCO₂e/m²/60 years). This suggests that when a comparative analysis is carried out using energy intensity rather than that of the life cycle performance as a performance proxy for evaluating refurbishments versus replacements - the analysis conclusion might be wrong.

Recommendation B: It is recommended that in the context of refurbishment versus replacement of existing buildings, it is imperative that a life cycle approach is being taken rather than energy intensity, and that emissions incurred by all stages in the life of a building are evaluated. Other performance proxies might provide an incomplete evaluation of performance and miss-inform stakeholders and design teams. It is concluded that incentivising building reuse can achieve quicker emissions reductions.

6.1.3. Life Cycle Performance Excluding the Demolition of Existing Building

When examining the embodied CO₂ of the refurbishment and replacement alternatives, the proposed computational framework in this research accounted for the demolished

and removed components and their embodied CO₂ (as covered in section 5.1.5). This is to acknowledge that the removal is part of the project - without it new developments cannot be built. There is, of course, difference between the demolished components in the refurbished and replacement buildings:

Refurbished buildings: are projects in which some parts (mostly finishes and windows) are taken out, but the main construction is retained.

Replacement buildings: are projects where existing buildings must be demolished first, and new buildings are built on the same site. This is in contrast to new buildings - buildings that are built on empty plots, where no demolition works are needed.

The figures of the embodied CO₂ of the removed components are likely to be significant: In examining the case studies in this research, the embodied CO₂ of the original building in a replacement scenario can add between 15-20% to the replacement's LCCF, while the embodied CO₂ of demolished components in refurbishments contributes between 5-10% of the LCCF values.

Figure 6.4 shows a comparison between the performance of the refurbishment and replacement scenarios of all case studies, in two different boundary scopes: one that accounts for the embodied CO₂ of demolished building components (Total LCCF) and one that does not (Total LCCF excluding demolitions).

Results show that in the case of the bungalow, refurbishments seem to perform better in both scenarios – both when the embodied CO₂ of demolished building components is added to the LCCF calculation and when it is not. However, in the terrace house and the block-of-flats case studies, while the performance of the replacement is similar or better than that of the refurbishment, this trend is reverse when adding the embodied CO₂ of the demolished components: refurbishment is better in that case.



Figure 6.4: Terrace house, bungalow and block-of-flats LCCF, excluding (left) and including (right) embodied CO₂ of demolished building components.

Recommendation C: To establish a complete understanding of the life cycle performance of refurbished buildings and their replacements, the embodied CO₂ of the building components that had been removed to enable the refurbishment or replacement needs to be added to the calculation, assuming these components are not recycled, as their embodied CO₂ is now wasted.

6.1.4. Limitations of Comparative Studies

The proposed computational framework in this research is based on the principle of a comparative case study (as explained in section 3.2). In order to carry out a meaningful comparison between the performance of different scenarios, it is important to compare alternatives with similar characteristics.

In this research, an attempt was made to examine the potential of using the proposed computational framework in a more realistic setting, where in the case of a replacement

– developers would like to extend the building rights. This scenario was tested in the ‘block-of-flats’ case study (section 5.4), where the refurbishment and replacement alternatives differed in their height and number of flats: the refurbishment building had four storeys (3 meters per storey height) while the replacement design had five (2.5 meters high each).

Lowering ceiling height for economic reasons might have further environmental consequences, in terms of building performance, as discussed in Chapter 5.4: the volume per flat becomes smaller, which requires less energy to heat it up. Furthermore, less materials are used for construction per flat, as the external and internal walls are lowered.

Another major design difference in the block-of-flats case study was access to flats: In the refurbishment building (Figure 5.41), access to the flats was designed through an external access corridor (which was excluded from the building overall floor area calculation), while in the replacements scenarios (Figure 5.42) a vertical core was designed, to allow tenants in and out of their homes. This made a typical floor in the replacement building around 10-15% larger than that of the refurbished building. These differences, which were the results of the strategy taken during the study design to enable a realistic, economic-driven analysis – have a clear impact on the buildings embodied CO² and costs.

Lastly, it is also acknowledged that some designs, generated by PLOOTO might have various shortcomings (e.g., architectural appearance, daylight distribution or others, however, the proposed framework is currently focused at minimising LCCF and LCC, and other optimisation criteria can be integrated in the future.

Recommendation D: Transparency is important in comparative studies, to enable a full understanding of the scope of the comparison and its limitations. This is particularly important in comparative studies where the compared objects were designed to have different properties that are likely to affect the comparison results.

6.2. Life Cycle Analysis Protocols

This section presents points for discussion that are related to the life cycle performance analysis protocols.

6.2.1. Life Cycle Analysis Protocol Assumptions and Limitations

As discussed in section 2.2.6, life cycle analysis of complex systems such as buildings, has inherent limitations and uncertainties, due to their initial scope and assumptions. As these limitations might have a significant impact on the analysis results, this section discusses the influence these might have on the study results.

A. Study Assumed Life Expectancy

This research has assumed that the expected life span of a building, based on the BRE's Green guide for specification (BRE, 2009b), was 60 years. Following this assumption, the investigation of all case studies showed that a refurbishment of existing buildings was the favourable design alternative, compared with their replacements. The case studies analysis also showed, however, that in terms of LCCF, the conclusion might be different if the assumed life expectancy would change – in some cases, the trend might be reversed: Some of the optimal block-of-flats replacements performed better than refurbishments after around 65 years, and some replacement terrace houses performed better than replacements after around 80 years.

Had the case studies time-frame was longer – the research results and conclusions (at least for the LCCF objective) might have been different. It is, therefore, important to acknowledge the uncertainty that lays within the analysis procedure, with regards to the buildings actual life span, when evaluating the case study results.

B. Embodied CO₂ and Cost Databases

To calculate the embodied CO₂ of building materials, this study used EPDs (Environmental Product Declarations) of specific building components, supplied by the product

manufacturers (these can be found in Appendix B). When these were not available – data was retrieved from Bath ICE – one of the most widely used embodied CO₂ data base for the UK. It is acknowledged that suppliers might differ in their production processes and that, similar building materials which were produced differently might vary in their embodied CO₂ values. It is also acknowledged that future manufacturing processes might be more efficient, in terms of CO₂ emissions. Therefore, in designing this research, the data that was used for the calculation of the construction embodied CO₂ values were the most up-to-date state of the art available data.

Building materials costs were collected from a combination of online manufacturer and supplier databases, as well as Spon's Architects' and Builders' Price Book (Langdon.D, 2013). It is acknowledged that building materials costs might differ across suppliers as well as that similar products might differ in their costs. It is also acknowledged that the costs of building materials in the future might vary and that new building materials might be introduced to the industry. Therefore, the approach during the research design was allowing a selection of widely used and affordable building materials (i.e. no rare or exceptionally expensive components were chosen), to allow a realistic analysis and evaluation of buildings life cycle costs.

C. Operational-related CO₂ and Costs

When calculating CO₂ emissions and costs associated with lighting, space and water heating, CO₂ emissions of fuels were based on the NCM (2013) and energy costs were based on UK Power (2017). These are the currently the most reliable sources for emissions and costs analysis.

It is acknowledged that future technologies, such as decarbonisation of the supply grid, the integration of renewable energy supply systems, a shift in the trends or availability of fuels or future technological discoveries might change the operational-related CO₂

emissions, but it is not possible to estimate the time these might take place or the actual effect they might have.

It is also acknowledged that the cost of energy is extremely volatile and tends to change rapidly. To accommodate this, and based on an analysis of historical energy costs increase and based on the BSRIA LCC guide (BSRIA, 2016), this research adopted an estimation of 10% rise in cost energy cost increase every 5 years.

D. Construction Works Costs

As described in Table 5.1, the LCC analysis in this research consisted of the costs related to initial building material costs, the costs of building materials replacements and the costs associated with lighting, space and water heating. The costs of construction work (labour) were not taken into account in this study. This is mainly because the duration of construction and the way construction works are priced have great variability across contractors.

It is noted that if the cost of construction works would have been added to the analysis, this would add to the “embodied costs” element of the analysis, which will make the difference between the “embodied costs” and “operational costs” (as in image 6.5, for example) even bigger.

E. Refurbished Building Orientation

As presented in section 5.1, the refurbishment scenario evaluated the impact of improvements applied to an existing case-study building. It is noted that all examined refurbishments were oriented towards the true north (as indicated in Figures 5.9, 5.25 and 5.41). This allowed the original refurbished buildings to have a large south-facing façade, which can maximise the potential use of solar gains and might lead to a reduction in energy consumption for heating, especially in the case of the block-of-flats, where all units had an optimal south-facing orientation. In two of the case studies (terrace house and bungalow), the replacement buildings were generated on a plot with the same size

and orientation as that of the refurbished one, while the shape of the plot in the case of the block-of-flats was slightly different (as presented in section 5.4.2). It is important to note that different initial lot orientation could have led to a different set of results.

F. The Number of Replacement Scenarios

As covered in 3.5.4, for the examination replacement scenarios, PLOOTO was used for the generation of non-biased spatial arrangements. In each case study, PLOOTO was stopped once it reached a certain number of designs, as it had been noted that similar layouts were generated.

Despite PLOOTO's capabilities for finding spatial arrangements, it is acknowledged that this study did not cover all possible design scenario within the given plot and design constraints, and that there might be some design solutions with better performance, that were not found by the algorithm.

Recommendation E: The assumptions and limitations of life cycle studies can have a significant impact on the study outcomes and conclusions. The following recommendations are set regarding assumptions in life cycle performance studies in the built environment:

Life expectancy: Current BRE guidelines assumes that the expected life of a residential building is 60 years. While this value can be adopted for assessment, in comparative studies, analysis should also show at what point in time performance trends are reversed.

Embodied CO₂ and Cost Databases: Depending on the analysis aims, data sources of CO₂ and costs should be selected carefully. When trying to identify general performance trends, designated CO₂ and costs can be used. In an analysis of detailed projects, and when building materials are known, EPDs or specific product costs would be more appropriate.

Operational-related CO₂ and Costs & Construction Works: Fluctuations in costs and CO₂ emissions of products and services is highly dependent on technologies. As production

processes are expected to be more efficient in the future – reduction of costs and emissions should be taken into account in the analysis as much as possible. Any clear and transparent set of assumptions should be set out.

It is pointed out that in light of the abovementioned limitations, the proposed computational framework is flexible to accommodate any future refinements: at any point, any of the input parameters (e.g.: cost, embodied CO₂, life expectancy etc.) can be modified to reflect a more accurate depiction of the model.

6.2.2. The LCC Calculation Method

As covered in section 2.2.5, the LCC protocol is a strict procedure which is primarily used by investors and decision makers for projects economic evaluation and feasibility tests. At its core, the procedure sums up the amount of capital needed at a starting point of a project (year 0), that will enable the funding of a project throughout its life. By incorporating a number of cost-related assumptions (discount factor, inflation rates, cost increases etc.), decision makers can raise the necessary funds at the early stage of the project, collect interest and absorb the costs of inflation and discounting over the years, to make sure that the project is funded throughout its assumed lifetime.

While the application of this approach is useful from an investor point of view, the LCC protocol creates a skewed projection of costs: due to discounting and inflation, the value of future costs in LCC analysis seem to be lower than their absolute values are at present.

Figure 6.5 shows a comparison between the LCC of the terrace house case study, using two different LCC calculation approaches:

- A. *Adjusted* – Where the LCC protocol (BS ISO-15686-5) is used, and when discounting and inflation are account for in calculating future energy costs and the cost of periodical repairs. This is the NPV calculation which seeks for a return for the initial investment (as covered in section 2.2.5).

- B. *Un-adjusted* – When discounting and inflation are excluded from the LCC calculations. This is a simpler calculation in which future payments are calculated based on the current value of money.

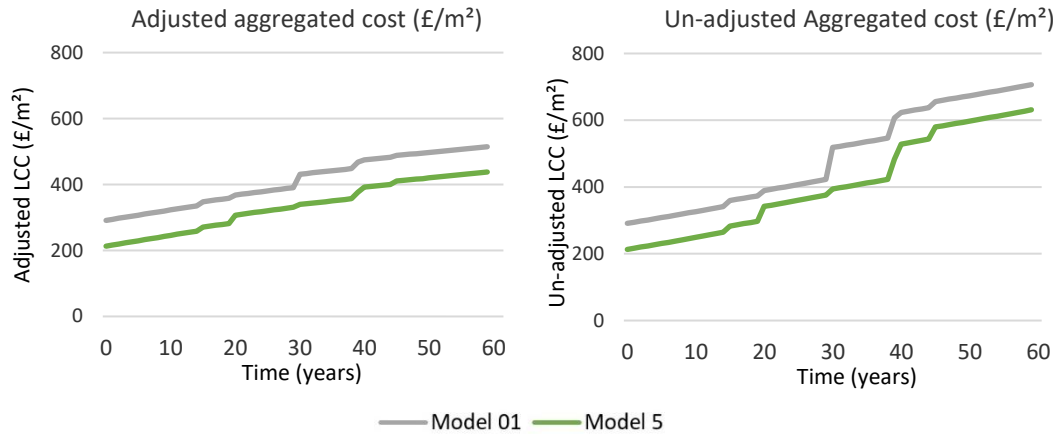


Figure 6.5: Adjusted (left) and un-adjusted (right) LCC aggregated costs of a terrace house refurbishment

The impact of discounting, inflation and increase in energy costs in traditional LCC analysis affect future costs rather than present ones. For this reason, the cost of the ‘product and construction’ phase (Phase A) in Figure 6.5 is the same in both charts – they occur at year 0 (present) when all initial assumptions are identical. When comparing the replacement and operational phases, though, it is evident that the proportion of replacement costs in the un-adjusted example are far higher than the adjusted ones.

Figure 6.6 shows a breakdown of the adjusted and un-adjusted LCC values, through the building’s life stages. Interestingly, the overall cost of energy use for lighting, space and water heating is relatively low compared to the initial capital investment and repairs. This means that operational energy use is a secondary contributor to the building’s life cycle costs, when examining both performance indicators. It is pointed out that as the optimal buildings have very good thermal performance. This mean that savings in energy costs are marginal compared to other LCC cost items – namely, the initial capital investments.

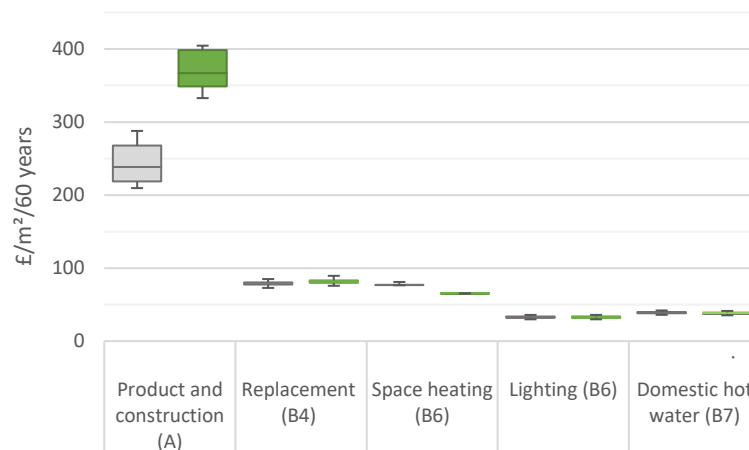
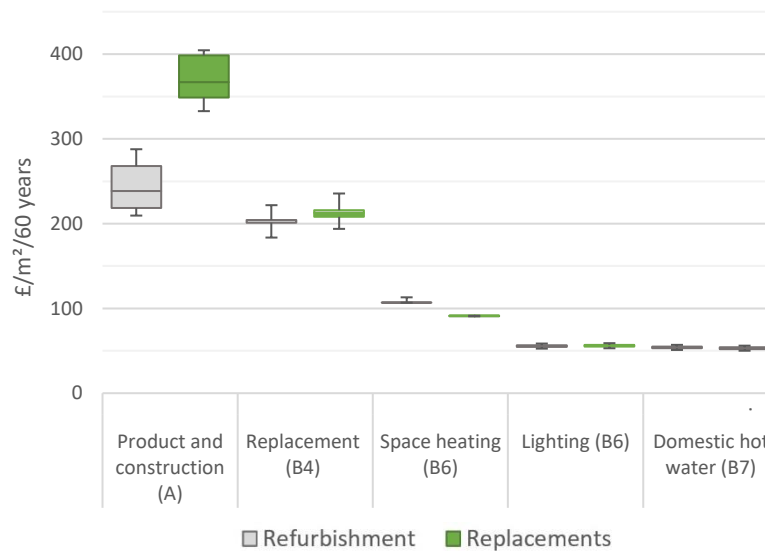
Adjusted LCC results (discount factor=0.03, energy price increased by 10% every 5 years)**Un-adjusted LCC results (no discount factor, no energy price increase)**

Figure 6.6: Adjusted (Top) and un-adjusted (bottom) LCC stages breakdown, by life cycle stage of a terrace house refurbishment

This is further expressed in Figure 6.7 – the ‘energy-in-use’ component (B6 + B7) are responsible for only around 36% of the LCCF of the refurbished terrace house and around 27% of its replacement’s LCC. It is also pointed out that the replacement alternative can save only £17/m²/60 years, compared to the refurbishment (or a total of between £2,000 - £5,000 for the entire 60 years in un-adjusted values) in their energy costs (B6+B7). This means that when evaluating the benefits of refurbishments and replacements and energy poverty – energy cost savings should play a secondary role.

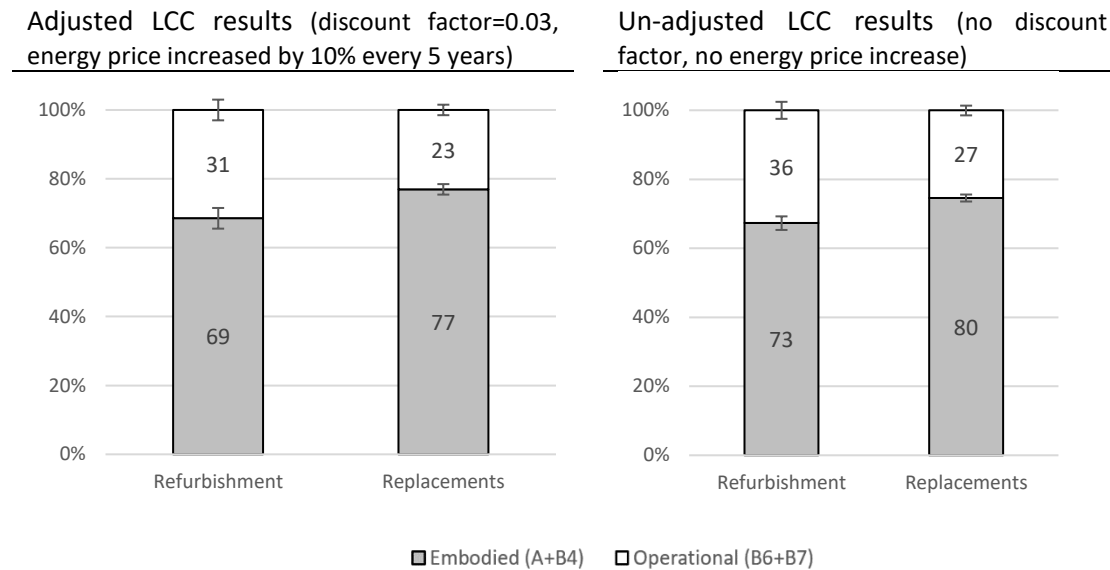


Figure 6.7: Adjusted (left) and un-adjusted (right) LCC embodied/operational breakdown of a terrace house refurbishment

Recommendation F: As the traditional LCC protocol is primarily designed to be used by investors – it accounts for discounting and inflation, to evaluate funding opportunities and potential future profit compared to other investment opportunities. The optimal buildings in both scenarios achieved very good thermal performance. As a result, savings in operational costs were marginal compared to the initial capital investments. While in this case analysis showed that in both adjusted and un-adjusted cases, operational costs were a secondary contributor to the buildings LCC, it is still recommended to be mindful when selecting LCC framework to ensure the method is appropriate for the analysis aims.

6.2.3. Life Cycle Performance Normalisation

Normalising building performance by floor area is useful as it is a relatively clear and easy-to-understand means for performance comparison. It is also often used at early stages of costing analysis and project feasibility assessments – where it was originally used – to quantify cost per unit of area. However, in the context of environmental performance, for a comparison to be accurate, the compared systems should have similar boundaries.

Though the differences between the refurbished and replaced buildings in the ‘block-of-flats’ had contributed to the difference in the buildings’ performance, the lowering of

ceiling height in the refurbishment scenario had provided an opportunity to explore the potential impact of different performance normalisation on the outcome of building performance analysis. Though building height in replacement buildings might be a controversial factor – it has been decided to adopt a realistic approach and acknowledge that this is a common practice in the industry. As the overall height of both the refurbishment and replacements was very similar (12-meter-high for the refurbishment and 12.5 meter for the replacement), Figure 6.2 shows a comparison between the pareto optimal refurbishments and replacements of the ‘block-of-flats’ case study, using the following metrics:

- A. normalisation by floor area (m^2)
- B. normalisation by volume (m^3)
- C. absolute values (not normalised)

Results show that in all three normalisations – the refurbishment scenario outperforms the replacement one. When normalising performance by floor area (Figure 6.8 left), some replacements actually perform better than some refurbishments, in terms of LCC, and have similar LCCF performance than other refurbishments. However, when normalising performance by volume (Figure 6.8 middle) - there seem to be a more significant difference in their performance – all refurbishments models perform better than replacements ones. This is sensible as the two buildings have similar heights, but the replacement scenario has extra embodied CO_2 of an entire floor’s windows and ceiling build-up, plus additional volume to maintain heat in. For the same reason, this trend becomes even more evident when comparing the absolute, un-normalised performance figures (Figure 6.8 right).

It is noted that the difference in performance between refurbishments and replacements when normalising by floor area can be between 0-15%, while in the case of absolute

values it can reach between 30 – 80%. This is an important issue to address when evaluating building performance to drive decision making.

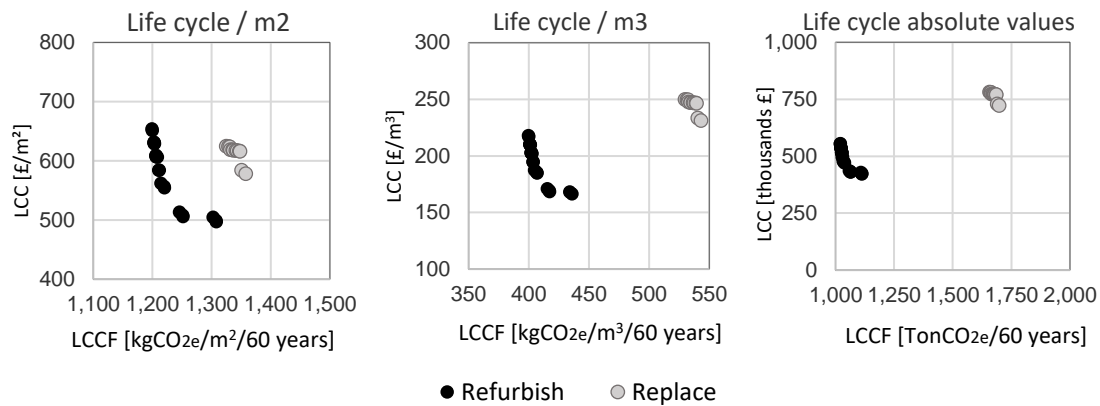


Figure 6.8: Life cycle normalisation: Floor area (left), volume (middle) and absolute value (right)

	Refurbishment		Replacement
Access	External access	corridor (excluded from overall building floor area)	“Point-block” – access through a vertical central core (included in overall building floor area)
Storeys	4		5
Floor height [m]	3		2.5
Overall height [m]	12		12.5

Table 6.1: ‘Block-of-flats’ refurbishment and replacement differences summary

Recommendation G: LCCF and LCC are frameworks that help stake holders and design teams in the decision-making process. As such, LCCF and LCC should be used in conjunction with other decision-making support frameworks and analysis tools when used in the built-environment, to account for other design-related aspects (financial, aesthetic, cultural, social, floor-to-floor height etc.)

6.3. Analysis of the Case Studies - Findings summary

This section summarises the findings of the case study buildings and discusses the implications of the case study results.

By examining the outputs of the three case study buildings analysis, the following summary is drawn:

A. Refurbish or Replace?

For all examined case study buildings and under the study scope and assumptions, the refurbishment scenario was found to be favourable when comparing the LCCF and LCC of the refurbished and replacement buildings.

It is pointed out that the results compare optimal solutions. This does not mean that any refurbishment design will perform better than any replacement design: when comparing the entire search spaces of the refurbishments and the replacements, some replacements perform better than many refurbishments. These cases, however, depend on the specific designs and they do not represent the optimal solutions.

Furthermore, while this research has found that optimal refurbishments were favourable than optimal replacements – this was the case specifically for the case studies that were examined in this research. It is pointed out that this research does not conclude that all optimal refurbishments will perform better than all optimal replacements, as each study might have different scope and potential refurbishment and replacement scenarios, which might significantly affect results:

B. Payback time

- For the Terrace house, results showed that in terms of LCCF, optimal refurbishments perform better than replacements for the examined life span, however, replacement models can outperform some refurbishment models after around 80 years.
- The refurbishment of Bungalow houses achieved significantly better performance than their replacements. The analysis showed that it should take a replacement around 250 years to outperform the refurbishment of an existing building.
- The refurbished of the block-of-flats achieved lower LCCF values than most replacements, and yet – some replacement buildings reach better performance after as fast as 65 years.

C. Embodied and Operational Performance

- For all case studies, the embodied CO₂ of the optimal replacements were around double than those of the optimal refurbishment.
- For all case studies, the operational-related CO₂ emissions had the largest contribution to the buildings LCCF: around 80-85% in the case of refurbishments and between 65-70% in the case of replacements.
- For all case studies, embodied capital costs had the largest contribution to the buildings LCC: around 70-75% in the case of refurbishments and around 76-80% in the case of replacements.
- When examining embodied CO₂, ground floor slabs seem to have a major contribution, in terms of LCCF, for both refurbishment and replacement. The embodied CO₂ range of a replacement ground floor slab was found to be around double than that of a refurbishment, due to the additional reinforcements and other structural elements.
- The embodied CO₂ of windows had the largest variation of all building components and materials. This is due to the difference between the embodied CO₂ of timber frame and uPVC frame windows and their life expectancy (as shown in Appendix A).
- The balance between the cost and embodied CO_{2e} of uPVC windows has shown that they have the poorest embodied performance.
- The cost of windows was a main contributor to the initial capital costs in both scenarios. Windows costs varied greatly due to the difference between the costs of timber and uPVC windows. Ground floor slabs were also found to have a major contribution to the initial capital cost of the replacement scenarios, while it had a relatively minor effect on refurbishments.

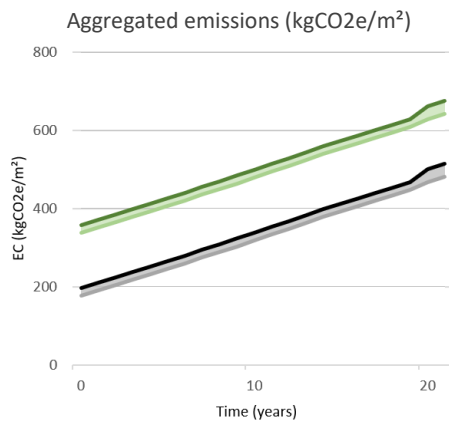
D. Refurbish or Replace – Short Term Analysis

As supporters of man-made climate change stress that quick actions are needed to cut CO₂ emissions to tackle climate change, an examination was carried to compare the

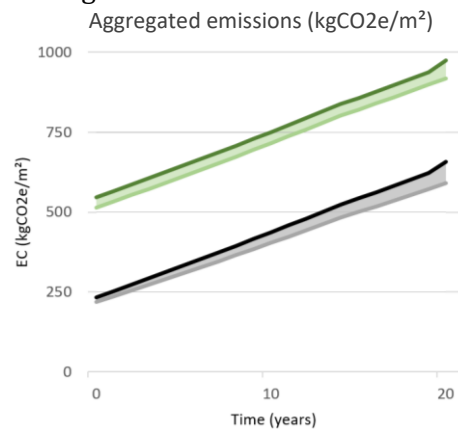
impact of the optimal refurbishments and replacements and evaluate their short-term (20 years) environmental impact, rather than their life cycle performance.

Figure 6.9 shows that refurbishments were shown to have significantly better performance in the short term: 20 years after refurbishments are carried out, they emit between 65-75% CO_{2e}, compared to replacements (510, 620 and 580 kgCO_{2e}/m² for the refurbishment of a terrace house, bungalow and block of flats, correspondently, and 650, 930 and 770 kgCO_{2e}/m² for their replacements). The main reason for this difference is associated to the embodied CO_{2e} emissions due to the replacement of existing materials – which needs to be transported to landfills, as well as the embodied CO_{2e} which is required for the actual construction. This embodied CO_{2e} is significantly lower in refurbishments, as building foundations and structure – highly CO_{2e} intensive elements – need to be procured in a replacement scenario.

A. Terrace house



B. Bungalow



C. Flats

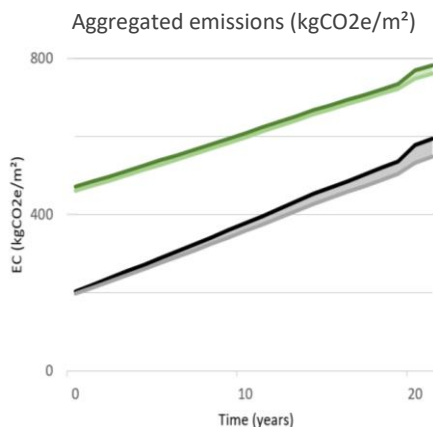


Figure 6.9: Short term (20-years) refurbishment/replacement LCCF comparison

Furthermore, Table 6.2 shows a performance comparison when excluding the emissions of the ‘replacement elements’ from the life cycle calculation (i.e., the elements that need to be placed at a landfill), or, in other words – embodied and operational performance only.

Table 6.2 implies that when comparing optimal refurbishments and replacements, the embodied performance in the refurbishment is far better than that of a replacement, as expected (since less material is involved in refurbishments). However, this table also reveals that, surprisingly, the operational performance in both scenarios is quite similar, presumably due to the relatively high thermal performance required by Part L for building refurbishments.

These findings echo those of Figure 6.8 and conclude that to get significant reduction in CO₂ emissions – refurbishments would generally perform better on a short term as they have significantly lower embodied CO₂e rates.

		Refurbishment		Replacement	
		kgCO _{2e} /m ²	(%)	kgCO _{2e} /m ²	(%)
Terrace	Embodied	136	12	247	20
	Operational	994	88	988	80
	Total	1,130		1,235	
Bungalow	Embodied	185	13	300	17
	Operational	1,235	87	1,465	83
	Total	1,420		1,765	
Flats	Embodied	122	10	279	21
	Operational	1,098	90	1,051	79
	Total	1,220		1,330	

Table 6.2: Embodied and Operational performance comparison (Embodied emissions = life stage A, operational emissions = life stages B4, B6 and B7)

Recommendation H: Refurbishments are preferable for short term emission reductions, as they have significantly lower Embodied CO₂e, and as the operational performance of refurbishments and replacements are quite similar when both are carried out following the relevant Part L regulation.

6.4. Future Developments in the Optimisation of Buildings for Life Cycle Performance

The implementation of optimisation of buildings, in terms of their life cycle analysis performance, is still at its early days. Life cycle analysis of complex systems such as buildings can involve a large number of assessment processes and procedures. This sub-chapter suggests and discusses some future developments, which might improve the accuracy and simplify the process of carrying a life cycle performance analysis in the built environment.

6.4.1. Dynamic Embodied CO₂ Databases

As covered in section 2.2.4, current life cycle CO₂ footprint analysis studies retrieve embodied CO₂ data either from pre-calculated energy and carb CO₂ on databases or from manufacturing Environmental Performance Declaration certificates (EPD`s). The two mechanisms have pros and cons: pre-calculated databases are relatively easy to find, and they are very simple to use, but they are quite generic as they show to be “material” level data rather than “product” level data. EPD`s, on the other hand, are considered to provide a more accurate description of the embodied CO₂ of particular products, but they are not widely available yet.

As the commissioning of EPD certificate is voluntary, it is expected that in the future, manufacturers would like to align with their competitors by improving their production process and display it to the public, in the form of an EPD.

Furthermore, retrieving EPD data is currently a relatively lengthy process. It requires browsing through different manufacturers websites and searching for the relevant documentations. There is currently no central database that gathers an industry-wide EPD certificates and enables an easy comparison and selection between them. In that respect, the BRE green guide for specification is a unique attempt for establishing such a

database, however, the database is not holds only a limited number of products information, and access is quite limited.

It is therefore expected that that an extensive database will be developed in the near future, summing up the total embodied CO₂ of a variety of building products and following a unified protocol, to ensure similar assessment scope for all products. This database will ideally be updated regularly and dynamically: whenever an EPD certificate for a new product is issued– it will automatically be added to the database and will be available for view by the users. This way, the database will enable users to undertake accurate comparative evaluations of the environmental impact of similar building materials.

6.4.2. Coupling BIM and Embodied CO₂ Evaluation and Life Cycle Analysis

Since Building Information Modelling (BIM) was introduced, it has revolutionised the building design industry by emphasizes the sharing of data and information, and in establishing communication channels between the various design parties. In 2011, the UK government decided to adopt BIM across the AEC industry.

Various studies have examined the ways BIM technologies could assist in addressing a range of sustainability-related issues, such as thermal modelling, embodied CO₂ calculations and life cycle performance assessment. Such integrations could improve the design process and make it more rigorous, by introducing various design, simulation and evaluation packages, all under the same tool.

Though the integration of environmental design concepts within BIM is becoming more readily available, it still suffers from integration issues, as the transition of models across the packages involves data loss, program errors and other interoperability problems.

It is expected that in the future, the integration between the different components of BIM will improve and the transition between one modelling package to another will be seamless. It is further expected that the LCA framework will be able to take advantage of

the BIM approach – a model as a database – and integrate embodied CO₂ data as an input parameter, to engage a more informed design process. As a first step for this, a REVIT plug-in application, for the automatic calculation of embodied CO₂, was prepared. The tool has been tested and used in practice and achieved positive response from the users.

6.4.3. Energy Consumption: Minimising the Impact of the Performance Gap

As operational energy consumption is a key component in the life cycle of buildings, the adoption of robust methods for estimating energy consumption in future designs is important in carrying an accurate analysis.

A performance gap – the difference between calculated and measured energy consumption – has received an increasing attention in recent years research and practice. It is noted that usage loads and profiles were based on NCM rather than on measured performance – which, among other factors (as discussed by Menezes *et al.*, 2012; de Wilde, 2014; Van Dronkelaar *et al.*, 2016) can contribute to uncertainty in the study's results. It is therefore expected that future research will lead to an even better understanding of the performance gap and to further reduction in its impact.

6.4.4. Computing and Processing Time

The current research has used an infrastructure network of a cloud computing system – UCL's Legion – a cluster of computers, available for use by UCL scholars, that enables a parallel computing capability for various computational procedures. In this case, multiple Legion cores was used for two main processes:

- A. Generative design – the generation of the different spatial arrangements in the format of an .idf file. In carrying the generative procedure, up to 6 cores were used in parallel for up to 20 minutes.
- B. Optimisation – the selection, modification and evaluation of the thermal models, and the identification of the pareto-optimal design solutions. In carrying the optimisation procedure, 60 cores were used in parallel for up to 2.5 hours.

As both procedures are resource-intensive, the following potential improvements are identified for enabling more efficient processing procedures:

- A. Improvements in computing capabilities - in the form of stronger processors on stand-alone computer devices. By improving processing efficiencies – the time spent on calculations will decrease.
- B. Improved cloud-computing solutions - a better integration of cloud-computing solutions will enable complex computational processes to be carried out in parallel. Greater availability of cloud systems could significantly reduce waiting times.
- C. Artificial Neural Networks (ANN) – By setting up a dataset exemplary models, an ANN application can be train for predicting evaluating the performance of un-tested models. The incorporation of ANN framework can lead to a significant cut in the need for computing resources and computing time.

6.4.5. Generative Design

As covered in section 2.4 and 2.5, current frameworks of generative design programming in architectural spatial arrangements are limited. Though architectural generative design is not yet highly developed, it is expected that this discipline will gain more and more attention, both in academia and in practice in the future. In that respect, the generative design procedure that has been developed for the purpose of this research fulfilled its aim – it resulted with a more comprehensive and realistic results than those found in the literature.

The proposed generative design procedure has proved adaptability for different design goals (terrace house/ bungalow / block-of-flats), however, there is still room for improvements.

Furthermore, since the scope of this research was limited for evaluating the refurbishment or replacements potential of residential buildings, the procedure focused on the generation of the layouts of residential buildings. Further development is required for the adaptation of the program for the generation of other building types.

Chapter summary:

This chapter sets out a discussion, following the findings of the case studies' analysis.

A. Implementation of the Proposed Computational Framework:

- Optimising the design of a terrace house by annual energy performance (the most commonly used performance metric) has resulted with a building that has almost 12% larger CO₂ footprint and which is around 15% (more than a total of £11,000, discounted, over 60 years, or £16,500, unadjusted) higher life cycle costs, compared to the actual optimal life cycle design.
- When comparing performance as space and water heating energy (kWh/m²/y) with life cycle carbon footprint (kgCO_{2e}/m²/60 years), two of the three case studies reached opposite results and conclusions.
- When examining refurbishments and replacements while excluding the embodied carbon related to demolitions – new buildings tend to have better performance (embodied + operational) due to the high level of insulation in the refurbishment, in accordance to Part L regulations.
- Encouraging re-use or design for de-construction can bring to quicker reductions in CO_{2e} emissions.

B. Life Cycle Analysis Protocols

- A discussion was set regarding the LCCF and LCC protocols assumptions and limitations. These included:
 - The assumed building life expectancy
 - The databases for calculating embodied carbon and costs

- The exclusion of construction works costs
- Figures show calculated performance (which will differ from measured)

The LCC calculation method includes discounting of future expenses. This protocol is often used by investors and management companies, but it results with a skewed projection of embodied costs versus operational costs, in present value of money. A series of tests evaluated the impact of discounting on LCC analysis.

- When comparing different normalisation approaches (floor area [kgCO₂e/m²/60 years], volume [kgCO₂e/m³/60 years] or total performance [tonsCO₂e/60 years]), results can vary significantly.

C. Analysis of the Case Studies - Findings summary

- It is concluded that for all case studies, and under the assumptions and limitations of this research, the optimal refurbishment, in terms of LCCF and LCC, outperformed optimal replacement. It is noted that this research compared the performance of optimal buildings in specific settings. This does not mean that all refurbishments outperform all replacements.
- LCCF payback times were found to be 80, 250 and 65 years, for the terrace house, bungalow and block-of-flats, respectively.
- All case studies indicated that the Embodied Carbon in replacements is around double than that of refurbishments, that operational-related CO₂ emissions have the largest contributor to the buildings carbon footprint and that initial construction capital costs have the largest contribution to the buildings life cycle costs.
- It is concluded that for short-term CO_{2e} reductions, refurbishments are likely to perform better, as they have significantly lower embodied CO₂ than

Replacements, and as their operational performance are quite similar to those of replacements, assuming both follow the relevant Part L regulation.

D. Future Developments in Optimisation of Buildings for Life Cycle

Performance

The study limitations were presented. Those included:

- Future developments in the life cycle performance of buildings were also discussed. Among those were:
 - Dynamic embodied carbon databases
 - Incorporating BIM in life cycle performance analysis

7. Conclusions and Future Work

In this chapter, the research conclusions and contribution to knowledge are presented, based on the results of the case studies and the discussion chapters, and opportunities for future research are set out. These address the three main themes of this research: The development of the computational framework, life cycle performance protocols and findings of the UK-based case studies.

This research aimed to develop, test and validate a computational framework through which an analysis could be carried out to determine which design alternative is favourable – an optimal refurbishment of existing buildings or their optimal replacement, in terms of the life cycle CO₂ and costs. The analysis process has included the following subprocesses: Automated form generation, selecting criteria for optimisation (build-ups and geometries), thermal analysis and optimisation. The development of the framework was followed by its implementation on the actual case study buildings.

7.1. Conclusions and Contribution to Knowledge

7.1.1. Establishing the Computational Framework for LCCF and LCC optimisation

Six core optimisation runs were carried out in total: the first three were used during the development, testing and validation of the proposed framework. The last three were the case study executions – complete life cycle performance comparisons, between refurbishments and replacements of case study buildings. Three further simulation runs were carried out as part of the discussion, to highlight issues that rose from the case study execution and results.

A. Integrating Computational Programming and Research of the Built Environment

The research computational framework (Section 3.1) included the integration of generative design programming, optimisation algorithms, thermal simulations and life

cycle performance evaluation frameworks (EN 15978:2011 for LCCF and BS ISO 15686-5 for LCC).

To enable the implementation of this research, the development, testing and validation of an innovative approach of research in the built environment had to be used. Two main computational tools were developed and, for the first time, used in the research of building design:

1. *The development of a designated computer application for the generation of spatial arrangements:* The development of a generative design application, as shown in this research began by reviewing the state-of-the-art literature of generative design approaches in building design and was followed by the development of an original generative design application. Since this is a research domain which is still at its infancy, and as it is expected that the discipline of generative design will expand and continue to grow, this research could contribute to the formation of this emerging field.
2. *The Integration between advanced computational techniques and environmental building design:* This research showed, for the first time, a successful integration between multiple computational techniques of various domains (generative design, genetic algorithms optimisation) and building environmental design techniques (LCA protocols, thermal simulations), all in a streamlined approach.

B. Establishing a Computational Framework for Optimising Buildings Refurbishments and Replacements by LCCF and LCC

The coupling of the abovementioned techniques was shown to be successful as an early design decision-making framework, for evaluating various LCCF and LCC aspects in refurbished buildings and their replacements. The outputs of the framework enabled to carry out an extended discussion to examine typical refurbishment versus replacement

assessment mechanisms, and an evaluation of the limitations of existing building performance protocols.

Detailed analysis included the use of LCCF and LCC as performance metrics, the impact of exclusion and inclusion of various life-stages on performance results, how assumed building life expectancy can affect analysis results and more.

It is pointed out that while the proposed framework is focused at minimising LCCF and LCC, other optimisation criteria (daylight, comfort, appearance) can potentially be integrated in it in future developments.

7.1.2. Life Cycle Protocols

The implementation of life cycle performance evaluation protocols might have various limitations which can have an importance impact on analysis results. This research addressed these issues by providing a transparent documentation of the research and analysis scope, and by carrying out a series of tests and analysis to evaluate the potential impact of the protocols potential shortcomings:

One of the key conclusions of this research is that by focusing on energy intensity (kWh/m²/year), the UK building regulations do not support the UK government commitment – which is reduction of CO₂ emissions. This is because the focus in the regulations is on the operational energy performance, rather than on life cycle CO₂ emissions.

The research examined how normalisation of performance and performance metrics can impact the interpretations of results. It was found that normalising annual performance by floor area and using energy intensity as a performance metric (kWh/m²/year), is a key issue in results interpretation, especially when comparing realistic refurbishment and replacement scenarios, where total floor area of refurbished buildings and their refurbishment might be different.

Based on the Green Guide for Specification guidelines (BRE, 2009b), this research assumed a 60 years as the case study buildings life span. This assumption is important as at least two of the case studies (the terrace house and the block of flats – sections 5.2 and 5.4), some replacement scenarios achieved better LCCF performance after as soon as 85 and 65 years, respectively (in the case of the bungalow case study, this happened after more than 250 years).

The LCC calculation procedure was also examined, and a comparison between LCC projections including and excluding discounting were examined. Results showed that in both cases, operational energy use was a secondary contributor to the building's life cycle costs. Still, it is important to select an appropriate LCC procedure to ensure it fits the study goals and evaluate the impact of different procedures when relevant.

7.1.3. Refurbishments and Replacements in the UK context

In answering the research questions, the following were found:

A. LCCF Benchmarks and Results

This research presented an analysis of a systematic literature review, which identified a range of acceptable Life Cycle Carbon Footprint performance (in units of $\text{kgCO}_2/\text{m}^2/60$ years) of more than 250 refurbished and new buildings, based on 48 peer-reviewed academic papers. The analysis of the CO_2 footprint of buildings in this scope was carried out, and a LCCF performance benchmark was set, for the first time, to visualize an accepted value for the LCCF of buildings. The review then presented a set of comparisons between the performance of refurbished and new buildings, to identify preferable design solution. This could assist future scholars and stake holders in evaluating the life cycle performance of their designs.

Furthermore, the case study results, as discussed in Chapters 5, and the discussion that was presented in chapter 6, further extend the state-of-the-art body of knowledge, in

relation to the LCCF and LCC of refurbishments versus replacements. The analysis can be further extended by other building types in various environments and markets, to establish a database of refurbishments and replacements case studies.

B. Comparing the LCCF and LCC of Refurbishments and Replacements

With regards to the main research aims and objectives, this research has shown that for the examined case studies, and under the assumption described in Chapter 5, the refurbishment scenarios were found to be favourable for all case studies. The refurbishment scenarios achieved 10%, 20%, and 10% smaller CO₂ footprint, for the terrace house, bungalow and block-of-flats respectively, and reached 20%, 30%, and 6% lower costs throughout the buildings life cycle. It is important to note that the abovementioned results are a summary of the comparison between the optimal solutions in each scenario. This implies that some replacement designs can have a better performance than some refurbishments, however, these would not be the optimal solutions.

The study has also concluded that to achieve quicker reductions, and in light of the urgency parts of the scientific community feels, refurbishments are generally preferable over replacements, as they often have lower embodied CO_{2e}, and their operational performance is similar to that of replacements (assuming both are Part L compliant). This means that when excluding emissions of replacements materials (i.e., materials that had been taken out from the original building) – though the operational performance of new buildings is often better – the difference in performance is often small. There is, however, a big difference in the levels of CO_{2e} that is embodied within the existing buildings and needs to be sent to a landfill, between the refurbishments and replacements.

For all case studies, operational energy consumption was identified as the main contributor to the buildings Life Cycle Carbon Footprint, whereas the initial construction cost was found to have the largest contribution to the buildings Life Cycle Cost. The main

reason for this difference was the difference between the operational-related CO₂ emissions and costs values (0.216 kgCO₂/kWh versus 0.045 £/kWh for gas and 0.519 kgCO₂/kWh versus 0.16 £/kWh for electricity), and their ratio compared to the embodied CO₂ and costs.

7.2. Future Work

A number of key issues are identified for further research at different levels of scopes. There is an opportunity for further research to deal with some of the research limitations, in particular those related to the life cycle performance analysis protocols (such as LCC calculation methods, embodied CO₂ and costs databases, future costs of products and services etc.). Other points relate to future development of technologies, and their potential integration with research in the built environment.

A. Advanced Technologies and Research Methods

Other research is proposed for the further development of the state-of-the-art research methods and tools used in this research, to extend the current body of knowledge.

1. The development of a generative design application was a key aspect of this research. This application, however, could only reach a certain level of development. Further research and development of generative design approaches, with a focus on their potential integration with sustainable design and engineering principles, could lead to a more extensive research of buildings sustainability and to the development of a new approach towards the design of low-carbon buildings.
2. Once a large enough set of data is produced and collected, tools and frameworks for evaluating the life cycle performance of buildings in a quicker way can be developed. These might address the issue in various hierarchies: the development of a designated tools for life cycle performance analysis in the built environment,

the development of regression analysis models or an analysing in a stock model scale. These could better inform decision makers and stake holders at different stages of developments.

3. As this research focused on the development and examination of a framework for identifying a favourable design solution when examining refurbishment and replacement of existing building, and while it evaluated some of the most common residential buildings in the UK, further research, involving other building architypes, uses, orientations and replacement scenarios can be carried. This can result with a more complete understanding of life cycle performance in buildings in general, and for the 'refurbishments vs replacements' discourse in particular.

B. Future Research of Buildings Life Cycle Performance

1. Embodied CO₂ databases are of great importance to in the studies of buildings carbon footprint. Though embodied CO₂ databases and protocols are developed rapidly, and though there are several attempts to standardise the embodied CO₂ evaluation process, there is still a need for a clear, comprehensive and evaluation and certification method, that will enable a better comparison of construction products across the industry. This might be in the form of either a system similar to legislative compliance, or a voluntary-based system, which relies primarily on incentivising manufacturers.
2. Life Cycle Carbon Footprint and Life Cycle Cost were selected as the building performance metric in this case study. This is, as explained in chapter 1, due to the global concerns with regards to CO₂ emissions, and the attempt to find the most economically viable way to achieve it. Further research could be carried, using the proposed methodology and approach, while taking into account other performance metric, e.g.: lighting levels, user comfort, health and well-being, productivity and others.

3. This research indicated that the choice of performance metrics can have a significant impact on the overall conclusions of building performance analysis. It also pointed out that the current industry standard metric normalisation – annual performance unit per unit of floor area (most often kWh/m²/year) – might depict a limited scope of building performance. It is, therefore, suggested to carry an extensive evaluation of a current performance metrics, and search for a more appropriate performance indicator that will enable a true understanding of building performance.

C. Refurbish or Replace?

This research had focused on the life cycle performance of refurbished building and their replacement in the context of the UK. Future work might include any of the following:

1. Extending the case study buildings to other residential building typologies within the UK context: end-of-terrace, co-living etc.
2. Extending the analysis to include other building types: Office buildings, schools or commercial spaces.
3. Using the proposed computational framework in a different geographic, climatic and economical context.

Once the number of the analysed case study increases and more data is available, opportunities to further develop research techniques and assessment frameworks (regression analysis, life cycle performance benchmarking etc.) will emerge. This could help to establish a more complete understanding of buildings life cycle performance, in general, and the research of refurbishment versus replacement – in particular.

8. References

- Abdallah, M., El-rayes, K. and Clevenger, C. (2015) 'Minimizing Energy Consumption and Carbon Emissions of Aging Buildings'. Elsevier B.V., 118, pp. 886–893. doi: 10.1016/j.proeng.2015.08.527.
- Akin, a. and Saka, M. P. (2015) 'Harmony search algorithm based optimum detailed design of reinforced concrete plane frames subject to ACI 318-05 provisions', *Computers & Structures*. Elsevier Ltd, 147, pp. 79–95. doi: 10.1016/j.compstruc.2014.10.003.
- Alaidroos, A. and Krarti, M. (2015) 'Optimal design of residential building envelope systems in the Kingdom of Saudi Arabia', *Energy & Buildings*. Elsevier B.V., 86, pp. 104–117. doi: 10.1016/j.enbuild.2014.09.083.
- Alba-rodríguez, M. D. *et al.* (2017) 'Building rehabilitation versus demolition and new construction : Economic and environmental assessment', *Environmental Impact Assessment Review*. Elsevier, 66(June), pp. 115–126. doi: 10.1016/j.eiar.2017.06.002.
- Ali, A. and Belal, M. (2007) 'Multiple ant colonies optimization for load balancing in distributed systems', *Icta'07*. Available at: <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.99.844&rep=rep1&type=pdf>.
- Amaratunga, R. *et al.* (2002) 'Qualitative and quantitative research in the built environment: Application of "mixed" research approach', *Work Study*, 51, pp. 17–31. doi: 10.1108/00438020210415488.
- Amaratunga, R. and Baldry, D. (2001) 'Case study methodology as a means of theory building: performance measurement in facilities management organisations', *International Journal of Productivity and Performance Management*, 50(3), pp. 95–104. doi: 10.1108/00438020110389227.
- Amini, F. and Ghaderi, P. (2013) 'Hybridization of harmony search and ant colony optimization for optimal locating of structural dampers', *Applied Soft Computing Journal*. Elsevier B.V., 13(5), pp. 2272–2280. doi: 10.1016/j.asoc.2013.02.001.
- ARUP (2010) *The Value of Existing Versus New Buildings*, Australian Capital Territory Government. Sydney.
- Asdrubali, F., Baldassarri, C. and Fthenakis, V. (2013) 'Life cycle analysis in the

construction sector: Guiding the optimization of conventional Italian buildings', *Energy and Buildings*. Elsevier B.V., 64, pp. 73–89. doi: 10.1016/j.enbuild.2013.04.018.

Ashworth, A. (1996) 'Estimating the life expectancies of building components in life-cycle costing calculations', *Structural Survey*, 14(2), pp. 4–8. doi: 10.1108/02630809610122730.

Assiego De Larriva, R. *et al.* (2014) 'A decision-making LCA for energy refurbishment of buildings: Conditions of comfort', *Energy and Buildings*. Elsevier B.V., 70, pp. 333–342. doi: 10.1016/j.enbuild.2013.11.049.

Baffes, J. *et al.* (2015) *The Great Plunge in Oil Prices : Causes , Consequences , and Policy Responses*. Available at: https://www.worldbank.org/content/dam/Worldbank/Research/PRN01_Mar2015_Oil_Prices.pdf.

Basbagill, J. P., Flager, F. L. and Lepech, M. (2014) 'A multi-objective feedback approach for evaluating sequential conceptual building design decisions', *Automation in Construction*. Elsevier B.V., 45, pp. 136–150. doi: 10.1016/j.autcon.2014.04.015.

Bayer, C. *et al.* (2010) 'Guide to Building Life Cycle Assessment in Practice', *American Institute of Architects*, pp. 1–193.

Bell, S. *et al.* (2014) *Making Decisions on the Demolition or Refurbishment of Social Housing Key points for making decisions 2 . Improving energy performance and, UCL Policy Briefing*. Available at: https://www.ucl.ac.uk/public-policy/sites/public-policy/files/migrated-files/Refurbishment_and_demolition_of_social_housing_FINAL.pdf.

BH Home Inspections (2018) *Building Materials Life Expectancy Chart*. Available at: <http://www.bhhomeinspections.com/building-materials-life-expectancy-chart/>.

Bichiou, Y. and Krarti, M. (2011) 'Optimization of envelope and HVAC systems selection for residential buildings', *Energy and Buildings*. Elsevier B.V., 43(12), pp. 3373–3382. doi: 10.1016/j.enbuild.2011.08.031.

Bin, G. and Parker, P. (2012) 'Measuring buildings for sustainability: Comparing the initial and retrofit ecological footprint of a century home - The REEP House', *Applied Energy*. Elsevier Ltd, 93, pp. 24–32. doi: 10.1016/j.apenergy.2011.05.055.

Blengini, G. A. and Di Carlo, T. (2010) 'The changing role of life cycle phases, subsystems

and materials in the LCA of low energy buildings', *Energy and Buildings*. Elsevier B.V., 42(6), pp. 869–880. doi: 10.1016/j.enbuild.2009.12.009.

Blum, C. and Roli, A. (2003) 'Metaheuristics in Combinatorial Optimization: Overview and Conceptual Comparison', *ACM Computing Surveys*, 35(3), pp. 268–308. doi: 10.1145/937503.937505.

Boardman, B. *et al.* (2005) '40% House report', *Environmental Change Institute*. Available at: <http://www.eci.ox.ac.uk/research/energy/downloads/40house/40house.pdf>.

Bojić, M., Miletić, M. and Bojić, L. (2014) 'Optimization of thermal insulation to achieve energy savings in low energy house (refurbishment)', *Energy Conversion and Management*, 84, pp. 681–690. doi: 10.1016/j.enconman.2014.04.095.

Bourke, K. *et al.* (2016) *RICS Professional Guidance, UK - Life cycle costing*. Available at: http://www.rics.org/Global/Life_cycle_costing_1st_edition_PGguidance_2016.pdf.

Bre (2012) *Refurbishing the Nation: Gathering the evidence, BRE - Building Research Establishment - The National Refurbishment Centre*. Available at: <https://www.bre.co.uk/page.jsp?id=2670>.

BRE (2009a) *Benchmarks for Predicting and Forecasting Construction Waste - Annex 3, BRE - Building Research Establishment*. Available at: www.randd.defra.gov.uk/Document.aspx?Document=WR0111_9108_FRA.pdf.

BRE (2009b) *The green guide to specification: an environmental profiling system for building materials and components, BRE - Building Research Establishment*. Available at: <http://books.google.com/books?hl=en&lr=&id=F1Ctcj6X4c4C&oi=fnd&pg=PR5&dq=The+Green+Guide+to+Specification+an+Environmental+Profiling+System+for+Building+Materials+and+Components+Third+Edition&ots=u2MDHb6aaJ&sig=OI7jSgCN87Fvf2y>.

BS ISO (2011) *BS EN 15978:2011 Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method*. BSI. Available at: <http://shop.bsigroup.com/ProductDetail/?pid=000000000030256638>.

BS ISO (2017) *BS ISO 15686-5:2017 Buildings and constructed assets. Service life planning. Life-cycle costing*. BSI. Available at: <https://shop.bsigroup.com/ProductDetail/?pid=000000000030263823>.

- Bullen, P. a. and Love, P. E. D. (2010) 'The rhetoric of adaptive reuse or reality of demolition: Views from the field', *Cities*. Elsevier Ltd, 27(4), pp. 215–224. doi: 10.1016/j.cities.2009.12.005.
- Caldas, L. (2008) 'Generation of energy-efficient architecture solutions applying GENE_ARCH: An evolution-based generative design system', *Advanced Engineering Informatics*, 22(1), pp. 59–70. doi: 10.1016/j.aei.2007.08.012.
- Caldas, L. G. (2001) *PhD Thesis: An Evolution-Based Generative Design System: Using Adaptation to Shape Architectural Form*. Available at: file:///C:/Users/Yair/Downloads/50059604-MIT.pdf.
- Calleja Rodríguez, G. *et al.* (2013) 'Uncertainties and sensitivity analysis in building energy simulation using macroparameters', *Energy and Buildings*, 67, pp. 79–87. doi: 10.1016/j.enbuild.2013.08.009.
- Chantrelle, F. P. *et al.* (2011) 'Development of a multicriteria tool for optimizing the renovation of buildings', *Applied Energy*. Elsevier Ltd, 88(4), pp. 1386–1394. doi: 10.1016/j.apenergy.2010.10.002.
- Chatzikonstantinou, I. (2014) 'A 3-Dimensional Architectural Layout Generation Procedure for Optimization Applications : DC-RVD', *Proceedings of the 2014 eCAADe Conference*, 1, pp. 287–296. Available at: http://cuminacad.scix.net/cgi-bin/works/Show?_id=ecaade2014_163&sort=DEFAULT&search=ioannis&hits=7.
- Chau, C. K., Leung, T. M. and Ng, W. Y. (2015) 'A review on Life Cycle Assessment , Life Cycle Energy Assessment and Life Cycle Carbon Emissions Assessment on buildings', 143, pp. 395–413. doi: 10.1016/j.apenergy.2015.01.023.
- Chen, Z., Lippke, B. and Stevens, N. (2005) 'Energy Consumption and Greenhouse Gas Emissions Related to the Use, Maintenance, and Disposal of a Residential Structure', *journal of the Society of Wood Science and Technology*, pp. 128–139. Available at: <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.554.5572&rep=rep1&type=pdf>.
- Chung, TT & Sun, T. (1994) 'Weight optimization for flexural reinforced concrete beams with static nonlinear response', *Structural Optimization*, 8(1), pp. 174–180. Available at: <https://link.springer.com/article/10.1007/BF01743315>.
- Churcher, D. and Tse, P. (2016) *Life Cycle Costing - A BSRIA Guide*. BSRIA. Available at:

<https://www.bsria.co.uk/download/product/?file=vYyl%2FLWRbuY%3D>.

CIOB (2013) 'APPG for EBE inquiry into Sustainable Construction and the Green Deal', *The Chartered Institute of Building*, (January). Available at: <http://cic.org.uk/admin/resources/charetered-institute-of-building.pdf>.

CML (2015) *CML*. Available at: <http://cml.leiden.edu/research/industrialecology/researchprojects/finished/new-dutch-lca-guide.html#the-handbook>.

Cobo, P., Moraes, E. and Simón, F. (2015) 'Inverse estimation of the non-acoustical parameters of loose granular absorbers by Simulated Annealing', *Building and Environment*, pp. 1–8. doi: 10.1016/j.buildenv.2015.05.009.

Cole, R. J. and Kernan, P. C. (1996) 'Life-cycle energy use in office buildings', *Building and Environment*, 31(4), pp. 307–317. doi: 10.1016/0360-1323(96)00017-0.

Colorni, A., Dorigo, M. and Maniezzo, V. (1991) 'Distributed Optimization by Ant Colonies', *Proceedings of the European Conference on Artificial Life*, (or D), pp. 134–142.

Communities & Local Government (2008) 'National Calculation Methodology (NCM) modelling guide (for buildings other than dwellings in England and Wales)', *Communities and local government*, (November), pp. 1–34.

Congradac, V. and Kulic, F. (2009) 'HVAC system optimization with CO2 concentration control using genetic algorithms', *Energy and Buildings*, 41(5), pp. 571–577. doi: 10.1016/j.enbuild.2008.12.004.

Consultants, P. (2000) 'Eco-indicator 99 Manual for Designers', *Ministry of Housing, Spatial Planning and the Environment*, (October). Available at: http://www.pre-sustainability.com/download/manuals/EI99_Manual.pdf.

Cooper, J. S. and Fava, J. a (2006) 'Life-Cycle Assessment Practitioner Survey', *Journal of Industrial Ecology*, 10(4), pp. 12–14. doi: 10.1162/jiec.2006.10.4.12.

Crawford, K. et al. (2014) *Demolition or Refurbishment of Social Housing ? A review of the evidence* *Demolition or Refurbishment of Social Housing ? A review of the evidence*.

Darke, P., Shanks, G. and Broadbent, M. (1998) 'Successfully completing case study research: Combining rigour, relevance and pragmatism', *Information Systems Journal*, 8(4), pp. 273–289. doi: 10.1046/j.1365-2575.1998.00040.x.

- Davis, J. P., Eusebgardt, K. M. and Binghamman, C. B. (2007) 'Develop Theory Through Simulation Methods', *Academy of Management Review*, 32(2), pp. 480–499. doi: 10.5465/AMR.2007.24351453.
- Delay, T., Farmer, S. and Jennings, T. (2009) 'Building the future , today: Transforming the economic and carbon performance of the buildings we work in', *Carbon Trust*, pp. 1–130. Available at: https://www.carbontrust.com/media/77252/ctc765_building_the_future_today.pdf.
- Department of Energy and Climate Change (2011) 'The Carbon Plan: Delivering our low carbon future', *Energy*, (December), p. 218. Available at: <http://www.decc.gov.uk/assets/decc/11/tackling-climate-change/carbon-plan/3702-the-carbon-plan-delivering-our-low-carbon-future.pdf>.
- Ding, G. (2013) 'Demolish or refurbish - environmental benefits of housing conservation', *Australasian Journal of Construction Economics and Building*, 13(2), pp. 18–34.
- Dixit, M. K. *et al.* (2010) 'Identification of parameters for embodied energy measurement: A literature review', *Energy and Buildings*, 42(8), pp. 1238–1247. doi: 10.1016/j.enbuild.2010.02.016.
- Dixit, M. K. *et al.* (2012) 'Need for an embodied energy measurement protocol for buildings: A review paper', *Renewable and Sustainable Energy Reviews*. Elsevier Ltd, 16(6), pp. 3730–3743. doi: 10.1016/j.rser.2012.03.021.
- 'doc11.pdf' (no date).
- Dodoo, A. and Gustavsson, L. (2013) 'Life cycle primary energy use and carbon footprint of wood-frame conventional and passive houses with biomass-based energy supply', *Applied Energy*. Elsevier Ltd, 112, pp. 834–842. doi: 10.1016/j.apenergy.2013.04.008.
- Dodoo, A., Gustavsson, L. and Sathre, R. (2014) 'Lifecycle carbon implications of conventional and low-energy multi-storey timber building systems', *Energy and Buildings*. Elsevier B.V., 82, pp. 194–210. doi: 10.1016/j.enbuild.2014.06.034.
- Dooley, K. (2002) 'Simulation research methods', *Companion to organizations*, pp. 829–848. Available at: <https://pdfs.semanticscholar.org/6f78/92adb5b2a07b20547cbdf5ca47aa6502c625.pdf>.

- Van Dronkelaar, C. *et al.* (2016) 'A Review of the Energy Performance Gap and Its Underlying Causes in Non-Domestic Buildings', 1(January), pp. 1–14. doi: 10.3389/fmech.2015.00017.
- Duarte, J. P. (2001) *PhD Thesis - Customizing Mass Housing: A Discursive Grammar for Siza's Malgueira Houses*. MIT. Available at: <https://dspace.mit.edu/handle/1721.1/8189>.
- Duda, M. and Shaw, J. S. (1997) *Life cycle assessment - A guide to approaches, experiences and information sources, Society*. European Environment Agency. doi: 10.1007/s12115-997-1054-x.
- Eisenhardt, K. M. (1989) 'Building Theories from Case Study Research.', *Academy of Management Review*, 14(4), pp. 532–550. doi: 10.5465/AMR.1989.4308385.
- Empty Homes Agency (2008) *New Tricks with Old Bricks: How reusing old buildings can cut carbon emissions*. Available at: <http://emptyhomes.com/wp-content/uploads/2011/06/New-Tricks-With-Old-Bricks-final-12-03-081.pdf>.
- Energy Saving Trust (2008) *Measurement of Domestic Hot Water Consumption in Dwellings*. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/48188/3147-measure-domestic-hot-water-consump.pdf.
- Enger, N. E. (1970) 'Simulation Case Study', in *Proceedings of the 1st symposium on Simulation of computer systems*, pp. 52–64.
- Eriksson, O. *et al.* (2007) 'Life cycle assessment of fuels for district heating: A comparison of waste incineration, biomass- and natural gas combustion', *Energy Policy*, 35(2), pp. 1346–1362. doi: 10.1016/j.enpol.2006.04.005.
- Erlandsson, M. and Levin, P. (2004) 'Environmental assessment of rebuilding and possible performance improvements effect on a national scale', *Building and Environment*, 39(12), pp. 1453–1465. doi: 10.1016/j.buildenv.2004.06.001.
- Erol, O. K. and Eksin, I. (2006) 'A new optimization method: Big Bang-Big Crunch', *Advances in Engineering Software*, 37(2), pp. 106–111. doi: 10.1016/j.advengsoft.2005.04.005.
- EToolGlobal (2017) *Typical Life Expectancy of Building Components*. Available at: <http://etoolglobal.com/wp-content/uploads/2015/10/BuildingComponentLifeExpectancy.pdf>.

European Commission - Joint Research Centre - Institute for Environment and Sustainability (2010) 'International Reference Life Cycle Data System (ILCD) Handbook : Analysing of existing Environmental Impact Assessment methodologies for use in Life Cycle Assessment', *European Commission*, p. 115.

European Commission (2013) *Energy Performance of Buildings Directive - Cost optimal calculations : UK report to European*. London.

Fay, R., Treloar, G. and Iyer-Raniga, U. (2000) 'Life-cycle energy analysis', *Building Research & Information*, 28(1), pp. 31–41. doi: 10.1080/096132100369073.

Feist, W. (1997) 'Life-Cycle Energy Analysis: Comparison of Low Energy House, Passive House, Self-Sufficient House', *Arbeitskreis kostengünstige Passivhäuser*, pp. 1–13.

Fesanghary, M., Asadi, S. and Geem, Z. W. (2012) 'Design of low-emission and energy-efficient residential buildings using a multi-objective optimization algorithm', *Building and Environment*. Elsevier Ltd, 49(1), pp. 245–250. doi: 10.1016/j.buildenv.2011.09.030.

Galle, P. (1981) 'An Algorithm for . Exhaustive Generation of Building Floor Plans', 24(12).

Garber, R. (2009) 'Optimisation stories: The impact of building information modelling on contemporary design practice', *Architectural Design*, 79(2), pp. 6–13. doi: 10.1002/ad.842.

Gaspar, P. L. and Santos, A. L. (2015) 'Embodied energy on refurbishment vs. demolition: A southern Europe case study', *Energy and Buildings*. Elsevier B.V., 87, pp. 386–394. doi: 10.1016/j.enbuild.2014.11.040.

Geem, Z. W., Kim, J. H. and Loganathan, G. . (2001) 'Optimization Algorithm', *Simulation*, 76:2, pp. 60–68. Available at:
<http://sim.sagepub.com/content/76/2/60.full.pdf+html?hwshib2=authn:1436956828:20150714%3A315fa138-0b39-47a2-8f8b-7954370983da:0:0:0:kMGLSNdBHXbG78sy1184qg==>.

Geletka, Vladimír; Sedláková, A. (2011) 'Impact of Shape of Buildings on Energy Consumption', *Energy*, pp. 1–8. Available at:
<http://ena.lp.edu.ua/bitstream/ntb/16694/1/47-Geletka-252-258.pdf>.

Ghazavi, M. and Bonab, S. (2011) 'Optimization of reinforced concrete retaining walls using ant colony method', ... *Symposium on Geotechnical Safety and Risk* (...), pp. 297–305.

Available at: http://vzb.baw.de/e-medien/geotechnical-safety-and-risk-2011/PDF/3_Risk_and_Reliability_in_Geotechnical_Engineering/3_14.pdf.

Gluch, P. and Baumann, H. (2004) 'The life cycle costing (LCC) approach: A conceptual discussion of its usefulness for environmental decision-making', *Building and Environment*, 39(5), pp. 571–580. doi: 10.1016/j.buildenv.2003.10.008.

Goldstein, B. P., Herbøl, M. and Figueroa, M. J. (2013) 'Gaps in tools assessing the energy implications of renovation versus rebuilding decisions', *Current Opinion in Environmental Sustainability*. Elsevier B.V., 5(2), pp. 244–250. doi: 10.1016/j.cosust.2013.03.005.

Guo, Z. and Li, B. (2017) 'Evolutionary approach for spatial architecture layout design enhanced by an agent-based topology finding system', *Frontiers of Architectural Research*. Elsevier B.V., 6(1), pp. 53–62. doi: 10.1016/j.foar.2016.11.003.

Gustafsson, S. (2000) 'Optimisation of insulation measures on existing buildings', *Energy and Buildings*, 33, pp. 49–55. Available at: <https://www.sciencedirect.com/science/article/pii/S0378778800000621>.

Gustavsson, L., Joelsson, A. and Sathre, R. (2010) 'Life cycle primary energy use and carbon emission of an eight-storey wood-framed apartment building', *Energy and Buildings*, 42(2), pp. 230–242. doi: 10.1016/j.enbuild.2009.08.018.

Hamdy, M., Hasan, A. and Siren, K. (2011) 'Applying a multi-objective optimization approach for Design of low-emission cost-effective dwellings', *Building and Environment*. Elsevier Ltd, 46(1), pp. 109–123. doi: 10.1016/j.buildenv.2010.07.006.

Hammond, G. and Jones, C. (2011) *Bath ICE - Inventory of Carbon & Energy V2.0*, Sustainable Energy Research Team (SERT) Department of Mechanical Engineering. Bath.

Han, G., Srebric, J. and Enache-Pommer, E. (2013) 'Variability of optimal solutions for building components based on comprehensive life cycle cost analysis', *Energy and Buildings*. Elsevier B.V., 79, pp. 223–231. doi: 10.1016/j.enbuild.2013.10.036.

Hanna, S. *et al.* (2010) 'Beyond simulation: designing for uncertainty and robust solutions', in *SimAUD 2010, Symposium on Simulation for Architecture and Urban Design at the 2010 Spring Simulation Multiconference*. doi: 10.1145/1878537.1878727.

Hasan, A. (1999) 'Optimizing insulation thickness for buildings using life cycle cost', *Applied Energy*, 63. Available at:

<https://www.sciencedirect.com/science/article/pii/S0306261999000239>.

Hasan, A., Vuolle, M. and Sire, K. (2008) 'Minimisation of life cycle cost of a detached house using combined simulation and optimisation', 43, pp. 2022–2034. doi: 10.1016/j.buildenv.2007.12.003.

Hawkins, D. and Mumovic, D. (2014) *PhD Thesis - Use of Integrated Simulation Application to Assess Life Cycle Carbon Impacts of University Building Redevelopment*. London.

Hillier, B. *et al.* (1976) 'Space syntax', *Environment and Planning B: Planning and Design*, 3(2).

HM Government (2010) *Approved Document L1B - Conservation of Fuel and Poer in Existing Dwellings*. Newcastle Upon Tyne.

HM Government (2016) *Approved Document L1A - Conservation of Fuel and Poer in New Dwellings*. Newcastle Upon Tyne.

HM Treasury and Treasury, H. M. (2011) *The Green Book - Appraisal and Evaluation in Central Government*, HM Treasury. Available at: http://www.hm-treasury.gov.uk/d/green_book_complete.pdf.

Horvath, A. (2004) 'Construction Materials and the Environment', *Annual Review of Environment and Resources*, 29(1), pp. 181–204. doi: 10.1146/annurev.energy.29.062403.102215.

Huijbregts, M. a. J. (1998) 'Application of uncertainty and variability in LCA Part I: A general framework for the analysis of uncertainty and variability in life cycle assessment', *The International Journal of Life Cycle Assessment*, 3(5), pp. 273–280. doi: 10.1007/BF02979835.

Ihm, P. and Krarti, M. (2012) 'Design optimization of energy efficient residential buildings in Tunisia', *Building and Environment*. Elsevier Ltd, 58, pp. 81–90. doi: 10.1016/j.buildenv.2012.06.012.

InterNACHI (2017) 'Typical " Life Expectancy " Table for common building materials & systems'. Available at: http://weberaccetta.com/wp-content/uploads/2017/04/Life_Expectancy_Table.pdf.

Islam, H. *et al.* (2014) 'Life Cycle Assessment and Life Cycle Cost Implications of Wall

- Assemblages Designs', *Energy and Buildings*. Elsevier B.V., 84, pp. 33–45. doi: 10.1016/j.enbuild.2014.07.041.
- ISO 14040 (2006) *Environmental management — Life cycle assessment — Principles and framework*. London. Available at: <https://www.iso.org/standard/37456.html>.
- ISO 14044 (2006) *Environmental management — Life cycle assessment — Requirements and guidelines*. London. Available at: <https://www.iso.org/standard/38498.html>.
- Itard, L. and Klunder, G. (2007) 'Comparing environmental impacts of renovated housing stock with new construction', *Building Research & Information*, 35(3), pp. 252–267. doi: 10.1080/09613210601068161.
- Jiao, Y., Lloyd, C. R. and Wakes, S. J. (2012) 'The relationship between total embodied energy and cost of commercial buildings', *Energy and Buildings*. Elsevier B.V., 52, pp. 20–27. doi: 10.1016/j.enbuild.2012.05.028.
- John, B. E. (2010) 'Reducing the Variability between Novice Modelers : Results of a Tool for Human Performance Modeling Produced through Human-Centered Design', (March), pp. 21–24.
- Kalay, Y. (2004) *Architecture's new media: Principles, theories, and methods of computer-aided design*. The MIT Press.
- Kolda, T. G., Lewis, R. M. and Torczon, V. (2003) 'Optimization by Direct Search : New Perspectives on Some Classical and Modern Methods', *Society for Industrial and Applied Mathematics*, 45(3), pp. 385–482. doi: 10.1137/S003614450242889.
- Kua, H. W. and Wong, C. L. (2012) 'Analysing the life cycle greenhouse gas emission and energy consumption of a multi-storied commercial building in Singapore from an extended system boundary perspective', *Energy and Buildings*. Elsevier B.V., 51, pp. 6–14. doi: 10.1016/j.enbuild.2012.03.027.
- Langdon, D. (2013) 'Spon's Architects' and Builders' Price Book', (Spon Press, 2 Park Square, Milton Park, Abingdon, Oxon OX14 4RN. ISBN 13:978-0-415-69077-5).
- Langston, Y. L. and Langston, C. A. (2008) 'Reliability of building embodied energy modelling: an analysis of 30 Melbourne case studies', *Construction Management and Economics*, 26(2), pp. 147–160. doi: 10.1080/01446190701716564.
- Li, J., Ng, S. T. and Skitmore, M. (2017) 'Review of low-carbon refurbishment solutions

- for residential buildings with particular reference to multi-story buildings in Hong Kong', *Renewable and Sustainable Energy Reviews*. Elsevier Ltd, 73(January), pp. 393–407. doi: 10.1016/j.rser.2017.01.105.
- Maile, T. *et al.* (2010) 'Tobias Maile, Martin Fischer, John Haymaker & Vladimir Bazjanac', *Environmental Engineering*, (August).
- March, J. G. and Lave, C. a (1975) *Introduction to Models in the Social Sciences*. Harpercollins College Div. Available at: <https://www.abebooks.co.uk/9780060438616/Introduction-Models-Social-Science-James-0060438614/plp>.
- Marson, F. and Musse, S. (2010) 'Automatic Real-Time Generation of Floor Plans Based on Squarified Treemaps Algorithm', *International Journal of Computer Games Technology*. doi: 10.1155/2010/624817.
- Martí, J. V. and González-Vidoso, F. (2010) 'Design of prestressed concrete precast pedestrian bridges by heuristic optimization', *Advances in Engineering Software*, 41(7–8), pp. 916–922. doi: 10.1016/j.advengsoft.2010.05.003.
- Menezes, A. C. *et al.* (2012) 'Predicted vs . actual energy performance of non-domestic buildings : using post-occupancy evaluation data to reduce the performance gap', *Applied Energy*, pp. 355–364. doi: 10.1016/j.apenergy.2011.11.075.
- Merrell, P., Schkufza, E. and Koltun, V. (2010) 'Computer-Generated Residential Building Layouts', *ACM Transactions on Graphics*, 29(6), pp. 1–12. doi: 10.1145/1866158.1866203.
- Merrell, P., Schkufza, E. and Vladlen, K. (2010) 'An Algorithm for Exhaustive Generation of Building Floor Plans', *Stanford University*. Available at: <https://graphics.stanford.edu/~pmerrell/floorplan-final.pdf>.
- Monahan, J. and Powell, J. C. (2011) 'An embodied carbon and energy analysis of modern methods of construction in housing: A case study using a lifecycle assessment framework', *Energy and Buildings*. Elsevier B.V., 43(1), pp. 179–188. doi: 10.1016/j.enbuild.2010.09.005.
- Mumovic, D. *et al.* (2009) *A Handbook of Sustainable Building Design and Engineering – An Integrated Approach to Energy, Health and Operational Performance of Buildings*. London: Earthscan. Available at: <http://discovery.ucl.ac.uk/149130/>.

Naboni, E. *et al.* (2013) 'Comparison Of Conventional, Parametric And Evolutionary Optimization Approaches For The Architectural Design Of Nearly Zero Energy Buildings', *13th Conference of International Building Performance Simulation Association*.

Nance, R. E. (1983) 'A tutorial view of Simulation model development', in *1983 Winter Simulation Conference*. Washington D.C: Virginia Polytechnic Institute and State University. Available at:
<https://vtechworks.lib.vt.edu/bitstream/handle/10919/20273/CS83025-R.pdf?sequence=3&isAllowed=y>.

Nassif, N., Kaji, S. and Sabourin, R. (2005) 'Optimization of HVAC Control System Strategy Using Two-Objective Genetic Algorithm', *HVAC&R Research*, 11(3), pp. 459–486. doi: 10.1080/10789669.2005.10391148.

NCM (2016) *National Calculation Methodology (NCM) modelling guide (for buildings other than dwellings in England)*. Available at: https://www.uk-ncm.org.uk/filelibrary/NCM_Modelling_Guide_2013_Edition_21October2016.pdf.

Nguyen, A.-T., Reiter, S. and Rigo, P. (2014) 'A review on simulation-based optimization methods applied to building performance analysis', *Applied Energy*. Elsevier Ltd, 113, pp. 1043–1058. doi: 10.1016/j.apenergy.2013.08.061.

Oikonomou, E. *et al.* (2012) 'Modelling the relative importance of the urban heat island and the thermal quality of dwellings for overheating in London', *Building and Environment*. Elsevier Ltd, 57(August 2003), pp. 223–238. doi: 10.1016/j.buildenv.2012.04.002.

Olivier, J. G. . *et al.* (2013) *Trends in global CO2 emissions 2013 report*. The Hague. Available at: http://edgar.jrc.ec.europa.eu/news_docs/pbl-2013-trends-in-global-co2-emissions-2013-report-1148.pdf.

Ostermeyer, Y., Wallbaum, H. and Reuter, F. (2013) 'Multidimensional Pareto optimization as an approach for site-specific building refurbishment solutions applicable for life cycle sustainability assessment', *International Journal of Life Cycle Assessment*, 18(9), pp. 1762–1779. doi: 10.1007/s11367-013-0548-6.

Padilla, J. J., Diallo, S. Y. and Tolk, A. (2011) 'Do We Need M & S Science ?', 4, pp. 161–166. Available at:
https://www.researchgate.net/profile/Andreas_Tolk/publication/225038246_Do_we_need_MS_science/links/0fcfd4fbef8f009cf1000000/Do-we-need-M-S-science.pdf.

- Page, E. H., Nance, R. E. and Arthur, J. D. (1994) *PhD Thesis: Simulation modeling methodology: principles and etiology of decision support*. Virginia Polytechnic Institute and State University. Available at: <https://vtechworks.lib.vt.edu/handle/10919/37951>.
- Panas, A. and Pantouvakis, J. . (2010) 'Evaluating Research Methodology in Construction Productivity Studies', *The Built & Human Environment Review*, 3(1), pp. 63–85. Available at: www.tbher.org/index.php/tbher/article/download/34/36.
- Panczak, T. D. and Cullimore, B. A. (2000) 'Parametric Thermal Analysis and Optimization Using Thermal DesktopSt'.
- Pappas, C. *et al.* (2004) *A Comparison of Heuristic, Meta-Heuristic and Optimal Approaches to the Selection of Conservation Area Networks*. Available at: <http://uts.cc.utexas.edu/~consbio/Cons/Tabu.pdf>.
- Paya, I. *et al.* (2008) 'Multiobjective optimization of concrete frames by simulated annealing', *Computer-Aided Civil and Infrastructure Engineering*, 23(8), pp. 596–610. doi: 10.1111/j.1467-8667.2008.00561.x.
- Poli, R., Langdon, W. and Mcphee, N. (2008) *A field guide to genetic programming*. Available at: http://www0.cs.ucl.ac.uk/staff/ucacbb/ftp/papers/poli08_fieldguide.pdf.
- Powell, M. J. D. (1973) 'On search directions for minimization algorithms', *Mathematical Programming*, 4(1), pp. 193–201. doi: 10.1007/BF01584660.
- Power, A. (2008) 'Does demolition or refurbishment of old and inefficient homes help to increase our environmental, social and economic viability?', *Energy Policy*, 36(12), pp. 4487–4501. doi: 10.1016/j.enpol.2008.09.022.
- Programming (2014) 'The nature of mathematical programming'. Available at: http://glossary.computing.society.informs.org/ver2/mpgwiki/index.php?title=Extra:Mathematical_programming.
- Rakkwamsu, P. *et al.* (2012) 'Evaluation of Greenhouse Gas Emission from Residential Buildings in Thailand', in *The Asian Conference on Sustainability, Energy & the Environment*. Available at: http://www.lindo.com/doc/online_help/lingo15_0/local_optima_vs__global_optima.htm.
- Ramesh, T., Prakash, R. and Shukla, K. K. (2010) 'Life cycle energy analysis of buildings: An overview', *Energy and Buildings*, 42(10), pp. 1592–1600. doi:

10.1016/j.enbuild.2010.05.007.

Raslan, R. and Davies, M. (2009) 'Results variability in accredited building energy performance compliance demonstration software in the UK: an inter-model comparative study', *Journal of Building Performance Simulation*, pp. 63–85. doi: 10.1080/19401490903477386.

Reidy, R. *et al.* (2005) *Guidelines for Life Cycle Cost Analysis*, Stanford University Land and Buildings. Available at: https://sustainable.stanford.edu/sites/default/files/Guidelines_for_Life_Cycle_Cost_Analysis.pdf.

Roberts, S. (2008) 'Altering existing buildings in the UK', *Energy Policy*, 36(12), pp. 4482–4486. doi: 10.1016/j.enpol.2008.09.023.

Rønning, A., Vold, M. and Nereng, G. (2009) *Refurbishment or Replacement of Buildings – What is Best for the Climate ?, Joint Actions on Climate Change*. Available at: https://www.researchgate.net/publication/267817457_Refurbishment_or_Replacement_of_Buildings_-_What_is_Best_for_the_Climate.

Sahab, M. G., Ashour, a. F. and Toropov, V. V. (2005) 'A hybrid genetic algorithm for reinforced concrete flat slab buildings', *Computers and Structures*, 83(8–9), pp. 551–559. doi: 10.1016/j.compstruc.2004.10.013.

Sargent, R. G. (1998) 'Verification and validation of simulation models', *1998 Winter Simulation Conference. Proceedings (Cat. No.98CH36274)*, 1(mimic). doi: 10.1109/WSC.1998.744907.

Sartori, I. and Hestnes, a. G. (2007) 'Energy use in the life cycle of conventional and low-energy buildings: A review article', *Energy and Buildings*, 39(3), pp. 249–257. doi: 10.1016/j.enbuild.2006.07.001.

Scheuer, C., Keoleian, G. a. and Reppe, P. (2003) 'Life cycle energy and environmental performance of a new university building: Modeling challenges and design implications', *Energy and Buildings*, 35(10), pp. 1049–1064. doi: 10.1016/S0378-7788(03)00066-5.

Schwartz, Y. *et al.* (2017) 'Integrated Building Performance Optimisation : Coupling Parametric Thermal Simulation Optimisation and Generative Spatial Design Programming', in *Proceedings of the 15th International Conference of the International Building Performance Simulation Association*. IBPSA, pp. 1222–1229. Available at:

http://www.ibpsa.org/proceedings/BS2017/BS2017_316.pdf.

Schwartz, Y., Raslan, R. and Mumovic, D. (2016) 'Implementing multi objective genetic algorithm for life cycle carbon footprint and life cycle cost minimisation: A building refurbishment case study', *Energy*, 97. doi: 10.1016/j.energy.2015.11.056.

El Semelawy, M., Nassef, a. O. and El Damatty, a. a. (2012) 'Design of prestressed concrete flat slab using modern heuristic optimization techniques', *Expert Systems with Applications*. Elsevier Ltd, 39(5), pp. 5758–5766. doi: 10.1016/j.eswa.2011.11.093.

Shaviv, E. and Gali, D. (1974) 'A model for space allocation in complex buildings.', *Build International*, 7(6), pp. 493–518.

Shekhawat, K. (2017) 'A computer-generated plus-shaped arrangement and its architectural applications', *Journal of Computational Design and Engineering*, 4, pp. 318–329. Available at: https://ac.els-cdn.com/S2288430016301518/1-s2.0-S2288430016301518-main.pdf?_tid=ae982281-83d4-4ef5-9184-6fe3cc63115e&acdnat=1531839971_6d99237c330c54e607f3928bbd256815.

SimaPro UK (2015) 'Personal Communication (Schwartz,Y)'.

Spekkink, D. (2005) *Performance Based Design: Bringing Vitruvius up to Date*, CIBdf – International Council for Research and Innovation in Building and Construction - Development Foundation. Available at: <http://www.irbnet.de/daten/iconda/CIB22233.pdf>.

Statista - the statistics portal (2018) *Average annual OPEC crude oil price from 1960 to 2018 (in U.S. dollars per barrel)*. Available at: https://inflationdata.com/Inflation/Inflation_Rate/Historical_Oil_Prices_Table.asp.

Sun, Y. *et al.* (2014) 'Uncertainty quantification of microclimate variables in building energy models', *Journal of Building Performance Simulation*, 1493, pp. 17–32. doi: 10.1080/19401493.2012.757368.

Sustainable Development Commission (2007) *Building houses or creating communities ?* Available at: http://www.sd-commission.org.uk/data/files/publications/SDC_SCP_report_2007.pdf.

Tae, S. *et al.* (2011) 'Life cycle environmental loads and economic efficiencies of apartment buildings built with plaster board drywall', *Renewable and Sustainable Energy Reviews*, 15(8), pp. 4145–4155. doi: 10.1016/j.rser.2011.06.009.

Tolk, A. (2010) 'Engineering Management Challenges for Applying Simulation as a Green Technology', *Lean and Green: Building a Sustainable Future through Engineering Management*. Available at: <http://ww2.odu.edu/~atolk/research/ASEM.045.pdf>.

Tuhus-Dubrow, D. and Krarti, M. (2010) 'Genetic-algorithm based approach to optimize building envelope design for residential buildings', *Building and Environment*. Elsevier Ltd, 45(7), pp. 1574–1581. doi: 10.1016/j.buildenv.2010.01.005.

UK Power (2017) *Energy Costs*. Available at: https://www.ukpower.co.uk/home_energy/tariffs-per-unit-kwh.

University of West England (2018) *Evolution of Building Elements*. Available at: https://fet.uwe.ac.uk/conweb/house_ages/elements/print.htm.

Velik, R. and Nicolay, P. (2015) 'Energy management in storage-augmented, grid-connected prosumer buildings and neighborhoods using a modified simulated annealing optimization', *Computers & Operations Research*. Elsevier, pp. 1–10. doi: 10.1016/j.cor.2015.03.002.

Vilches, A., Garcia-martinez, A. and Sanchez-monta, B. (2017) 'Life cycle assessment (LCA) of building refurbishment : A literature review', *Energy & Buildings*, 135, pp. 286–301. doi: 10.1016/j.enbuild.2016.11.042.

Wainwright, J. and Mark, M. (2013) *Environmental Modelling: Finding Simplicity in Complexity*. John Wiley & Sons Ltd. doi: 10.1002/9781118351475.

Wainwright, J. and Mulligan, M. (2012) *Environmental Modelling*. John Wiley & Sons Ltd. Available at: http://faculty.ksu.edu.sa/Almutaz/Documents/Enviro_courses/ENVS-531/Environmental_Modelling_Finding_Simplicity_in_Complexity.pdf.

Wang, B., Xia, X. and Zhang, J. (2014) 'A multi-objective optimization model for the life-cycle cost analysis and retrofitting planning of buildings', *Energy and Buildings*. Elsevier B.V., 77, pp. 227–235. doi: 10.1016/j.enbuild.2014.03.025.

Wang, L., Mathew, P. and Pang, X. (2012) 'Uncertainties in energy consumption introduced by building operations and weather for a medium-size office building', *Energy and Buildings*. Elsevier B.V., 53, pp. 152–158. doi: 10.1016/j.enbuild.2012.06.017.

Wang, X., Altan, H. and Kang, J. (2015) 'Parametric study on the performance of green residential buildings in China', *Frontiers of Architectural Research*. Elsevier, 4(1), pp. 56–67. doi: 10.1016/j.foar.2014.06.007.

- de Wilde, P. (2014) 'The gap between predicted and measured energy performance of buildings: A framework for investigation', *Automation in Construction*, 41, pp. 40–49. doi: 10.1016/j.autcon.2014.02.009.
- Winther, B. N. and Hestnes, a. G. (1999) 'Solar versus green: The analysis of a Norwegian row house', *Solar Energy*, 66(6), pp. 387–393. doi: 10.1016/S0038-092X(99)00037-7.
- Woodward, D. G. (1997) 'Life cycle costing—Theory, information acquisition and application', *International Journal of Project Management*, 15(6), pp. 335–344. doi: 10.1016/S0263-7863(96)00089-0.
- WRAP (2008) *WRAP Net Waste Tool - Guide to Reference Data, Version 1.0*. Available at: [http://nwtool.wrap.org.uk/Documents/WRAP NW Tool Data Report.pdf](http://nwtool.wrap.org.uk/Documents/WRAP_NW_Tool_Data_Report.pdf).
- Wright, J. . (1986) *PhD Thesis - The optimised design of HVAC systems*. Loughborough. Available at: <https://dspace.lboro.ac.uk/dspace-jspui/bitstream/2134/7291/2/DX088981.pdf>.
- Wright, J. a., Loosemore, H. a. and Farmani, R. (2002) 'Optimization of building thermal design and control by multi-criterion genetic algorithm', *Energy and Buildings*, 34(9), pp. 959–972. doi: 10.1016/S0378-7788(02)00071-3.
- Yang, X.-S. (2011) 'Metaheuristic Optimization'. Available at: http://www.scholarpedia.org/article/Metaheuristic_Optimization.
- Yang, X.-S. and Deb, S. (2010) 'Engineering Optimisation by Cuckoo Search', *Int. J. Mathematical Modelling and Numerical Optimisation*, 1(4), p. 17. doi: 10.1504/IJMMNO.2010.035430.
- Yang, X. S. (2009) 'Harmony search as a metaheuristic algorithm', *Studies in Computational Intelligence*, 191, pp. 1–14. doi: 10.1007/978-3-642-00185-7_1.
- Yeo, D. and Gabbai, R. D. (2011) 'Sustainable design of reinforced concrete structures through embodied energy optimization', *Energy and Buildings*. Elsevier B.V., 43(8), pp. 2028–2033. doi: 10.1016/j.enbuild.2011.04.014.
- Yin, R. K. (2014) *Case study research : design and methods*. 5th edn. London: Los Angeles ; London : SAGE. Available at: https://books.google.co.uk/books?id=FzawIAdilHkC&printsec=frontcover&source=gbs_ViewAPI&redir_esc=y#v=onepage&q&f=false.

Zeigler, B. P. and Kim, T. G. (2000) *Theory of modeling and simulation: integrating discrete event and continuous complex dynamic systems*. 2nd edn. Academic Press.

Available at:

https://books.google.co.uk/books/about/Theory_of_Modeling_and_Simulation.html?id=REzmYOQmHuQC&printsec=frontcover&source=kp_read_button&redir_esc=y#v=onepage&q&f=false.

Zhang, Y. (2012) 'Use jEPlus as an efficient building design optimisation tool', *CIBSE ASHRAE Technical Symposium, Imperial College*, (April), pp. 1–12. Available at:

<http://www.jeplus.org/wiki/doku.php?id=research:publications>.

Zott, C. (2003) 'Dynamic capabilities and the emergence of intraindustry differential firm performance: Insights from a simulation study', *Strategic Management Journal*, 24(2), pp. 97–125. doi: 10.1002/smj.288.

- Appendices -

Appendix A – Building Components and Materials Data

Material/ component	Thickness (m)	kgCO _{2e} /kg ¹	Density (kg/m ³) ²	Life Span (years) ³	Waste rate (%) ⁴	Cost (GBP/m ²) ⁵
Plasterboard	0.0125	0.302	668	Life	22.5	8
Ins Mineral Wool 100mm	0.1	*1.37	19.5	Life	15	6
Ins XPS 50mm	0.05	2.82	35	Life	5	11
Ins EPS 100mm	0.1	3.17	25	Life	5	7
Ins Mineral Wool 75mm	0.075	1.37	19.5	Life	15	5
Ins EPS 75mm	0.075	3.17	25	Life	5	6
Concrete 100	0.1	0.107	2400	Life	5	25
Ground London Clay	1	0	0	Life	0	0
Brick	0.102	0.158	1550	Life	20	45
Aerated Block	0.1	0.28	600	Life	20	20
Screed	0.2	0.25	2300	Life	5	150
Clad Cement Board	0.008	0.724	1700	45	8	45
Clad Aluminum	0.0009	11	2700	43	8	35
Roof Ceramic Tiles	0.013	0.48	1600	45	8	35
Roof Slate	0.008	0.04	2850	74	8	75
Roof Fiber Cement	0.008	2.8	1700	45	8	50

¹ kgCO_{2e} values were calculated based on data combined from EPDs (Appendix B) and Bath ICE (Hammond & Jones, 2011)

² Density values were retrieved from online resources: <http://www.rfcafe.com/references/general/density-building-materials.htm> <https://www.quora.com/What-are-the-densities-of-some-common-materials-used-in-buildings> <https://theconstructor.org/building/density-construction-materials/13531/> https://www.engineeringtoolbox.com/density-materials-d_1652.html

³ Life expectancies are based on data from EToolGlobal (2017), InterNACHI (2017) and BH Home Inspection (2018).

⁴ Waste rates are based on data from WRAP (2008) and BRE (2009).

⁵ Cost data was calculated based on data combined from Spon's Architects' and Builders' Price Book (Langdon.D, 2013)

Material/ component	Thickness (m)	kgCO _{2e} /kg ¹	Density (kg/m ³) ²	Life Span (years) ³	Waste rate (%) ⁴	Cost (GBP/m ²) ⁵
Flooring						
Hardwood	0.02	1.09	750	39	10	70
Flooring						
Laminated wood	0.005	3.3	600	20	10	25
Flooring						
Carpet (nylon)	0.01	4.5	400	10	5	38
MDF	0.01	1.2	700	39	10	6
Plaster (render)	0.02	0.13	668	39	5	15
Window (Aluminum frame)	-	232.5	-	44	5	450
Window (PVC frame)	-	95.8	-	35	5	220
Window (Timber frame)	-	15.0	-	50	5	600
Timber (wall construction)	-	2.67*	550	100	5	3.68*
Timber (Floor construction)	-	3.05*	550	100	5	4.2*

Table A-A.1: Building components and materials data

¹ kgCO_{2e} values were calculated based on data combined from EPDs (Appendix B) and Bath ICE (Hammond & Jones, 2011)

² Density values were retrieved from online resources: <http://www.rfcafe.com/references/general/density-building-materials.htm> <https://www.quora.com/What-are-the-densities-of-some-common-materials-used-in-buildings> <https://theconstructor.org/building/density-construction-materials/13531/> https://www.engineeringtoolbox.com/density-materials-d_1652.html

³ Life expectancies are based on data from EToolGlobal (2017), InterNACHI (2017) and BH Home Inspection (2018).

⁴ Waste rates are based on data from WRAP (2008) and BRE (2009).

⁵ Cost data was calculated based on data combined from Spon's Architects' and Builders' Price Book (Langdon.D, 2013)

* Values calculated for m² of construction elements at 0.4m horizontal and 1.2m vertical intervals

Appendix B – EPD Sources

- BRE Baker, E. (2017a) *EPD Statement of Verification for Casement Window*. Available at: http://www.greenbooklive.com/filelibrary/EN_15804/EPD/BREG-EN-EPD-000160.pdf.
- BRE Baker, E. (2017b) *EPD Statement of Verification Screed*. Available at: <http://www.greenbooklive.com/pdffdocs/en15804epd/BREGENEPD000156.pdf>.
- BRE Baker, E. (2017c) *EPD Statement of Verification Wood for Good BRE Global Scheme Document SD207 This declaration is for :* Available at: <https://woodforgood.com/assets/Downloads/EPD/BREGENEPD000124.pdf>.
- BRE Critien, L. (2016) *EPD Statement of Verification Rock Mineral Wool Insulation 33 - 45 kg / cu . m*. Available at: https://www.knaufinsulation.com/sites/ki_com/files/BREGENEPD000095.pdf.
- BRE Hughes, D. (2014a) *EPD Statement of Verification: BDA generic brick*. Available at: http://www.greenbooklive.com/filelibrary/EN_15804/EPD/BDA-EN-EPD-0002.3.pdf.
- BRE Hughes, D. (2014b) *EPD Statement of Verification Thermalite Autoclaved Aerated Concrete Block*. Available at: http://www.greenbooklive.com/filelibrary/EN_15804/EPD/Hanson-EN-EPD-0001.5.pdf.
- Flemish Institute for Technological Research (2012) *EPD Statement of Verification Clay roof tiles 1 Declaration of general information*. Available at: https://docmh.com/the-philosophy-of-money.html?utm_source=environmental-product-declaration-epd-clay-roof-tiles.
- IBU Bossenmayer, H. J. (2015) *EPD Statement of Verification Carpet Tiles*. Available at: <http://www.millikencarpet.com/en-gb/sustainability/Documents/EPDCertificate - Naturally Drawn%2C Glazed Clay%2C Clerkenwell.pdf>.
- IBU Horst J, B. (2012) *EPD Statement of Verification Fibre Cement*. Available at: <https://www.cembrit.nl/media/5118/epd-cem-2012111-e-cladding.pdf>.
- IBU Horst J, B. (2017) *EPD Statement of Verification Expanded Polystyrene (EPS)*. Available at: <http://www.gph.at/images/gph/produkt/oekologie/EPD-EUM-20160275-IBG1-EN.pdf>.
- IBU Horst J, B. (2018a) *EPD Statement of Verification Cold-formed aluminium sheet for exterior applications*. Available at: <https://epd-online.com/PublishedEpd/Download/8582>.
- IBU Horst J, B. (2018b) *EPD Statement of Verification Expanded Polystyrene (EPS) Foam Insulation EUMEPS (region Scandinavia)*. Available at: <https://www.jackon.no/assets/FileUploads/EPD-Jackopor-150.pdf>.
- Morris, R. (2018) *EPD Statement of Verification - 12.5mm Gyproc WallBoard*. Available at: <http://environdec.com/en/Detail/epd506>.
- Soum-Fontez, T. (2015) *EPD Statement of Verification Fibre-cement slates January 2015*. Available at: <https://www.marleyeternit.co.uk/~media/Files/Environment-Files/FC-slate-EPD---Birkdale-and-Rivendale.pdf?la=en>.

Appendix C – Refurbishment Scenarios – Build-ups and Building

Components

Roof ¹		U-Value [w/m ² k]				
#	Combination					
0	1a	Ceramic tiles	Mineral wool (200)	Structure	Plasterboard + Render	0.17
1	1b	Ceramic tiles	XPS (100)	Structure	Plasterboard + Render	0.2
2	1c	Ceramic tiles	EPS (200)	Structure	Plasterboard + Render	0.16
3	2a	Slate	Mineral wool (200)	Structure	Plasterboard + Render	0.17
4	2b	Slate	XPS (100)	Structure	Plasterboard + Render	0.20
5	2b	Slate	EPS (200)	Structure	Plasterboard + Render	0.16
6	3a	Fibre cement	Mineral wool (200)	Structure	Plasterboard + Render	0.17
7	3b	Fibre cement	XPS (100)	Structure	Plasterboard + Render	0.2
8	3c	Fibre cement	EPS (200)	Structure	Plasterboard + Render	0.16

External Wall ¹		U-Value [w/m ² k]				
#	Combination					
0	A	Brick + Structure	Mineral wool (100)	Plasterboard + Render		0.29
1	B	Brick + Structure	XPS (100)	Plasterboard + Render		0.19
2	C	Brick + Structure	EPS (100)	Plasterboard + Render		0.28
3	1a	Aluminum cladding	Mineral wool (100)	Brick + Structure	Plasterboard + Render	0.29
4	1b	Aluminum cladding	XPS (100)	Brick + Structure	Plasterboard + Render	0.19
5	1b	Aluminum cladding	EPS (100)	Brick + Structure	Plasterboard + Render	0.28
6	2a	Plasterboard + Render	Mineral wool (100)	Brick + Structure	Plasterboard + Render	0.28
7	2b	Plasterboard + Render	XPS (50)	Brick + Structure	Plasterboard + Render	0.27
8	2c	Plasterboard + Render	EPS (100)	Brick + Structure	Plasterboard + Render	0.27

Party Wall¹

#	Combination			
0	a	Brick + Structure	Mineral wool (100)	Plasterboard + Render
1	b	Brick + Structure	XPS (50)	Plasterboard + Render
2	c	Brick + Structure	EPS (100)	Plasterboard + Render

¹ The shaded elements are kept for the refurbishment

Ground Floor¹

#	Combination							U-Value [w/m ² k]
0	1a	Wood flooring	MDF	Mineral wool (100)	Sub-structure	Screed	Ground	0.22
1	1b	Wood flooring	MDF	XPS (50)	Sub-structure	Screed	Ground	0.24
2	1c	Wood flooring	MDF	EPS (100)	Sub-structure	Screed	Ground	0.22
3	2a	Carpet	MDF	Mineral wool (100)	Sub-structure	Screed	Ground	0.22
4	2b	Carpet	MDF	XPS (50)	Sub-structure	Screed	Ground	0.25
5	2c	Carpet	MDF	EPS (100)	Sub-structure	Screed	Ground	0.22
6	A	Concrete	Screed	Mineral wool (100)	Ground			0.23
7	B	Concrete	Screed	XPS (50)	Ground			0.25
8	C	Concrete	Screed	EPS (100)	Ground			0.22

Internal Partitions¹

#	Combination				
0	Plasterboard	Mineral wool (75)	Structure	Plasterboard	Render

Internal Floor/ Ceiling¹

#	Combination						U-Value [w/m ² k]
0	1a	Carpet	MDF	Structure	Mineral wool (100)	Plasterboard + Render	0.29
1	1b	Carpet	MDF	Structure	XPS (50)	Plasterboard + Render	0.33
2	1c	Carpet	MDF	Structure	EPS (100)	Plasterboard + Render	0.28
3	2a	Wood flooring	MDF	Structure	Mineral wool (100)	Plasterboard + Render	0.28
4	2b	Wood flooring	MDF	Structure	XPS (50)	Plasterboard + Render	0.35
5	2c	Wood flooring	MDF	Structure	EPS (100)	Plasterboard + Render	0.29
6	3a	Laminated floor	MDF	Structure	Mineral wool (100)	Plasterboard + Render	0.3
7	3b	Laminated floor	MDF	Structure	XPS (50)	Plasterboard + Render	0.36
8	3c	Laminated floor	MDF	Structure	EPS (100)	Plasterboard + Render	0.3

Windows

#	Combination
0	Aluminium frame double glazed
1	uPVC frame double glazed
2	Timber frame double glazed

¹ The shaded elements are kept for the refurbishment

Appendix D – Replacement Scenarios – Build-ups and Building Components

Roof

#	Combination					U-Value [w/m ² k]
0	1a	Ceramic tiles	Mineral wool (200)	Structure	Plasterboard + Render	0.11
1	1b	Ceramic tiles	XPS (100)	Structure	Plasterboard + Render	0.13
2	1c	Ceramic tiles	EPS (200)	Structure	Plasterboard + Render	0.11
3	2a	Slate	Mineral wool (200)	Structure	Plasterboard + Render	0.11
4	2b	Slate	XPS (100)	Structure	Plasterboard + Render	0.13
5	2c	Slate	EPS (200)	Structure	Plasterboard + Render	0.11
6	3a	Fibre cement	Mineral wool (200)	Structure	Plasterboard + Render	0.11
7	3b	Fibre cement	XPS (100)	Structure	Plasterboard + Render	0.13
8	3c	Fibre cement	EPS (200)	Structure	Plasterboard + Render	0.11

External Wall

#	Combination					U-Value [w/m ² k]
0	1a	Brick	Mineral wool (100)	Plasterboard + Render		0.16
1	1b	Brick	XPS (100)	Plasterboard + Render		0.13
2	1c	Brick	EPS (100)	Plasterboard + Render		0.16
3	2a	Aluminum cladding	Mineral wool (200)	Plasterboard + Render		0.17
4	2b	Aluminum cladding	XPS (100)	Plasterboard + Render		0.13
5	2c	Aluminum cladding	EPS (200)	Plasterboard + Render		0.16
6	3a	Plasterboard + Render	Mineral wool (100)	Aerated block	Plasterboard + Render	0.15
7	3b	Plasterboard + Render	XPS (50)	Aerated block	Plasterboard + Render	0.17
8	3c	Plasterboard + Render	EPS (100)	Aerated block	Plasterboard + Render	0.15

Party Wall

#	Combination			
0	a	Brick	Mineral wool (100)	Plasterboard + Render
1	b	Brick	XPS (50)	Plasterboard + Render
2	c	Brick	EPS (100)	Plasterboard + Render

Ground Floor

#	Combination							U-Value [w/m²k]
0	1a	Wood flooring	MDF	Mineral wool (100)	Sub-structure	Screed	Ground	0.13
1	1b	Wood flooring	MDF	XPS (50)	Sub-structure	Screed	Ground	0.11
2	1c	Wood flooring	MDF	EPS (100)	Sub-structure	Screed	Ground	0.13
3	2a	Carpet	MDF	Mineral wool (100)	Sub-structure	Screed	Ground	0.1
4	2b	Carpet	MDF	XPS (50)	Sub-structure	Screed	Ground	0.11
5	2c	Carpet	MDF	EPS (100)	Sub-structure	Screed	Ground	0.13
6	A	Concrete	Screed	Mineral wool (100)	Ground			0.1
7	B	Concrete	Screed	XPS (50)	Ground			0.11
8	C	Concrete	Screed	EPS (100)	Ground			0.13

Internal Partitions

#						
0	Plasterboard	Mineral wool (75)	Structure	Plasterboard	Render	

Internal Floor/ Ceiling

#	Combination						U-Value [w/m ² k]
0	1a	Carpet	MDF	Structure	Mineral wool (100)	Plasterboard + Render	0.29
1	1b	Carpet	MDF	Structure	XPS (50)	Plasterboard + Render	0.33
2	1c	Carpet	MDF	Structure	EPS (100)	Plasterboard + Render	0.28
3	2a	Wood flooring	MDF	Structure	Mineral wool (100)	Plasterboard + Render	0.28
4	2b	Wood flooring	MDF	Structure	XPS (50)	Plasterboard + Render	0.35
5	2c	Wood flooring	MDF	Structure	EPS (100)	Plasterboard + Render	0.29
6	3a	Laminated floor	MDF	Structure	Mineral wool (100)	Plasterboard + Render	0.3
7	3b	Laminated floor	MDF	Structure	XPS (50)	Plasterboard + Render	0.36
8	3c	Laminated floor	MDF	Structure	EPS (100)	Plasterboard + Render	0.3

Windows

#	
0	Aluminium frame double glazed
1	uPVC frame double glazed
2	Timber frame double glazed

External floor							U-Value [w/m ² k]
#	Combination						
0	1a	Wood flooring	MDF	Structure	Mineral wool (200)	Plasterboard + Render	0.16
1	1b	Wood flooring	MDF	Structure	XPS (100)	Plasterboard + Render	0.19
2	1c	Wood flooring	MDF	Structure	EPS (200)	Plasterboard + Render	0.16
3	2a	Laminated floor	MDF	Structure	Mineral wool (200)	Plasterboard + Render	0.16
4	2b	Laminated floor	MDF	Structure	XPS (100)	Plasterboard + Render	0.2
5	2c	Laminated floor	MDF	Structure	EPS (200)	Plasterboard + Render	0.16
6	A	Carpet	MDF	Structure	Mineral wool (200)	Plasterboard + Render	0.16
7	B	Carpet	MDF	Structure	XPS (100)	Plasterboard + Render	0.19
8	C	Carpet	MDF	Structure	EPS (200)	Plasterboard + Render	0.16

Appendix E – Thermal Zones and Schedules

Bedrooms

Occupancy

Activity Database

Activity Daily Schedule Weekly Schedule Annual Schedule General

Daily Schedules

Object selector: **Dwell_DomBed_Occ_Hol**

General

Name: **Dwell_DomBed_Occ_Hol** Description:

Type: FRACTION

Category: OCCUPANCY

Source: BRE estimates

Hours	0 to 1	1 to 2	2 to 3	3 to 4	4 to 5	5 to 6	6 to 7	7 to 8	8 to 9	9 to 10	10 to 11	11 to 12	12 to 13	13 to 14	14 to 15	15 to 16	16 to 17	17 to 18	18 to 19	19 to 20	20 to 21	21 to 22	22 to 23	23 to 24
	1	1	1	1	1	1	1	0.5	0.25	0	0	0	0	0	0	0	0	0	0	0	0	0.25	0.75	

Shortcut to fill hours

From: To: Value: Apply

☐ tick if it is for holiday

Record: 221 of 4054 No Filter Search

Lighting – 2.8W/m²

Activity Database

Activity Daily Schedule Weekly Schedule Annual Schedule General

Daily Schedules

Object selector: **Dwell_DomBed_Light_Wkdy**

General

Name: **Dwell_DomBed_Light_Wkdy** Description:

Type: FRACTION

Category: LIGHTING

Source: BRE estimates

Hours	0 to 1	1 to 2	2 to 3	3 to 4	4 to 5	5 to 6	6 to 7	7 to 8	8 to 9	9 to 10	10 to 11	11 to 12	12 to 13	13 to 14	14 to 15	15 to 16	16 to 17	17 to 18	18 to 19	19 to 20	20 to 21	21 to 22	22 to 23	23 to 24
	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0.2	0.2	0.2	0.2	0	

Shortcut to fill hours

From: To: Value: Apply

☐ tick if it is for holiday

Record: 1035 of 4054 No Filter Search

Equipment – 3.58 W/m²

Activity Database

Activity Daily Schedule Weekly Schedule Annual Schedule General

Daily Schedules

Object selector: **Dwell_DomBed_Equip_Wkdy**

General

Select a different Daily Schedule

Name: **Dwell_DomBed_Equip_Wkdy** Description:

Type: FRACTION

Category: EQUIPMENT

Source: BRE estimates

Hours	0 to 1	1 to 2	2 to 3	3 to 4	4 to 5	5 to 6	6 to 7	7 to 8	8 to 9	9 to 10	10 to 11	11 to 12	12 to 13	13 to 14	14 to 15	15 to 16	16 to 17	17 to 18	18 to 19	19 to 20	20 to 21	21 to 22	22 to 23	23 to 24
	0.0699	0.0699	0.0699	0.0699	0.0699	0.0699	0.0699	0.535	1	0.535	0.0699	0.0699	0.0699	0.0699	0.0699	0.0699	0.0699	0.30245	0.535	0.7675	1	1	0.7675	0.3024

Shortcut to fill hours

From: To: Value:

Apply

☐ tick if it is for holiday

Record: 14 1843 of 4054 No Filter Search

Setpoint – Heating at 18°C

Activity Database

Activity Daily Schedule Weekly Schedule Annual Schedule General

Daily Schedules

Object selector: **Dwell_DomBed_Heat_Wkdy**

General

Select a different Daily Schedule

Name: **Dwell_DomBed_Heat_Wkdy** Description:

Type: TEMPERATURE

Category: TEMPERATURE SET POINTS

Source: BRE estimates

Hours	0 to 1	1 to 2	2 to 3	3 to 4	4 to 5	5 to 6	6 to 7	7 to 8	8 to 9	9 to 10	10 to 11	11 to 12	12 to 13	13 to 14	14 to 15	15 to 16	16 to 17	17 to 18	18 to 19	19 to 20	20 to 21	21 to 22	22 to 23	23 to 24
	18	18	18	18	18	18	18	18	18	12	12	12	12	12	12	12	12	12	12	18	18	18	18	18

Shortcut to fill hours

From: To: Value:

Apply

☐ tick if it is for holiday

Record: 14 2887 of 4054 No Filter Search

Kitchen

Occupancy

Activity Database

Activity Daily Schedule Weekly Schedule Annual Schedule General

Daily Schedules

Object selector: **Dwell_DomKitchen_Occ_Wkdy**

General

Name: **Dwell_DomKitchen_Occ_Wkdy** Description:

Type: FRACTION

Category: OCCUPANCY

Source: BRE estimates

Hours

0 to 1	0	6 to 7	0	12 to 13	0	18 to 19	0
1 to 2	0	7 to 8	1	13 to 14	0	19 to 20	0.2
2 to 3	0	8 to 9	1	14 to 15	0	20 to 21	0.2
3 to 4	0	9 to 10	1	15 to 16	0	21 to 22	0.2
4 to 5	0	10 to 11	0	16 to 17	0	22 to 23	0.2
5 to 6	0	11 to 12	0	17 to 18	0	23 to 24	0

Shortcut to fill hours

From: To: Value: Apply

☐ tick if it is for holiday

Record: 233 of 4054 No Filter Search

Lighting – 8 W/m²

Activity Database

Activity Daily Schedule Weekly Schedule Annual Schedule General

Daily Schedules

Object selector: **Dwell_DomKitchen_Light_Wkdy**

General

Name: **Dwell_DomKitchen_Light_Wkdy** Description:

Type: FRACTION

Category: LIGHTING

Source: BRE estimates

Hours

0 to 1	0	6 to 7	0	12 to 13	0	18 to 19	0
1 to 2	0	7 to 8	1	13 to 14	0	19 to 20	1
2 to 3	0	8 to 9	1	14 to 15	0	20 to 21	1
3 to 4	0	9 to 10	1	15 to 16	0	21 to 22	1
4 to 5	0	10 to 11	0	16 to 17	0	22 to 23	1
5 to 6	0	11 to 12	0	17 to 18	0	23 to 24	0

Shortcut to fill hours

From: To: Value: Apply

☐ tick if it is for holiday

Record: 1047 of 4054 No Filter Search

Equipment – 30.28 W/m²

Activity Database

Activity Daily Schedule Weekly Schedule Annual Schedule General

Daily Schedules

Object selector: **Dwell_DomKitchen_Equip_Wkdy**

General

Name: **Dwell_DomKitchen_Equip_Wkdy** Description:

Type: FRACTION

Category: EQUIPMENT

Source: BRE estimates

Hours

0 to 1	0.0661	6 to 7	0.0661	12 to 13	0.0661	18 to 19	0.0661
1 to 2	0.0661	7 to 8	1	13 to 14	0.0661	19 to 20	0.2528
2 to 3	0.0661	8 to 9	1	14 to 15	0.0661	20 to 21	0.2528
3 to 4	0.0661	9 to 10	1	15 to 16	0.0661	21 to 22	0.2528
4 to 5	0.0661	10 to 11	0.0661	16 to 17	0.0661	22 to 23	0.2528
5 to 6	0.0661	11 to 12	0.0661	17 to 18	0.06605	23 to 24	0.0661

Shortcut to fill hours

From: To: Value:

Apply

☐ tick if it is for holiday

Record: 1855 of 4054 No Filter Search

Setpoint – Heating at 18°C

Activity Database

Activity Daily Schedule Weekly Schedule Annual Schedule General

Daily Schedules

Object selector: **Dwell_DomKitchen_Heat_Wkdy**

General

Name: **Dwell_DomKitchen_Heat_Wkdy** Description:

Type: TEMPERATURE

Category: TEMPERATURE SET POINTS

Source: BRE estimates

Hours

0 to 1	12	6 to 7	18	12 to 13	12	18 to 19	18
1 to 2	12	7 to 8	18	13 to 14	12	19 to 20	18
2 to 3	12	8 to 9	18	14 to 15	12	20 to 21	18
3 to 4	12	9 to 10	18	15 to 16	12	21 to 22	18
4 to 5	12	10 to 11	12	16 to 17	12	22 to 23	18
5 to 6	18	11 to 12	12	17 to 18	18	23 to 24	12

Shortcut to fill hours

From: To: Value:

Apply

☐ tick if it is for holiday

Record: 2910 of 4054 No Filter Search

Dining room

Occupancy

Activity Database

Activity Daily Schedule Weekly Schedule Annual Schedule General

Daily Schedules

Object selector: **Dwell_DomDining_Occ_Wkdy**

General

Name: **Dwell_DomDining_Occ_Wkdy** Description:

Type: FRACTION

Category: OCCUPANCY

Source: BRE estimates

Hours			
0 to 1	0	6 to 7	0.25
1 to 2	0	7 to 8	1
2 to 3	0	8 to 9	1
3 to 4	0	9 to 10	0.25
4 to 5	0	10 to 11	0
5 to 6	0	11 to 12	0
12 to 13	0	13 to 14	0
14 to 15	0	15 to 16	0
16 to 17	0	17 to 18	0
18 to 19	0.5	19 to 20	1
20 to 21	1	21 to 22	0.3
22 to 23	0	23 to 24	0

Shortcut to fill hours

From: To: Value:

Apply

☐ tick if it is for holiday

Record: 230 of 4054 No Filter Search

Lighting – 4.1 W/m²

Activity Database

Activity Daily Schedule Weekly Schedule Annual Schedule General

Daily Schedules

Object selector: **Dwell_DomDining_Light_Wkdy**

General

Name: **Dwell_DomDining_Light_Wkdy** Description:

Type: FRACTION

Category: LIGHTING

Source: BRE estimates

Hours			
0 to 1	0	6 to 7	1
1 to 2	0	7 to 8	1
2 to 3	0	8 to 9	1
3 to 4	0	9 to 10	1
4 to 5	0	10 to 11	0
5 to 6	0	11 to 12	0
12 to 13	0	13 to 14	0
14 to 15	0	15 to 16	0
16 to 17	0	17 to 18	0
18 to 19	1	19 to 20	1
20 to 21	1	21 to 22	1
22 to 23	0	23 to 24	0

Shortcut to fill hours

From: To: Value:

Apply

☐ tick if it is for holiday

Record: 1045 of 4054 No Filter Search

Equipment – 3.06 W/m²

Activity Database

Activity Daily Schedule Weekly Schedule Annual Schedule General

Daily Schedules

Object selector: **Dwell_DomDining_Equip_Wkdy**

General

Name: **Dwell_DomDining_Equip_Wkdy** Description:

Type: FRACTION

Category: EQUIPMENT

Source: BRE estimates

Hours	0 to 1	1 to 2	2 to 3	3 to 4	4 to 5	5 to 6	6 to 7	7 to 8	8 to 9	9 to 10	10 to 11	11 to 12	12 to 13	13 to 14	14 to 15	15 to 16	16 to 17	17 to 18	18 to 19	19 to 20	20 to 21	21 to 22	22 to 23	23 to 24
	0.0816	0.0816	0.0816	0.0816	0.0816	0.0816	0.3112	1	1	0.3112	0.0816	0.0816	0.0816	0.0816	0.0816	0.0816	0.0816	0.08157	0.5408	1	1	0.3571	0.0816	0.0816

Shortcut to fill hours

From: To: Value: Apply

☐ tick if it is for holiday

Record: 1853 of 4054 No Filter Search

Setpoint – Heating at 18°C

Activity Database

Activity Daily Schedule Weekly Schedule Annual Schedule General

Daily Schedules

Object selector: **Dwell_DomDining_Heat_Wkdy**

General

Name: **Dwell_DomDining_Heat_Wkdy** Description:

Type: TEMPERATURE

Category: TEMPERATURE SET POINTS

Source: BRE estimates

Hours	0 to 1	1 to 2	2 to 3	3 to 4	4 to 5	5 to 6	6 to 7	7 to 8	8 to 9	9 to 10	10 to 11	11 to 12	12 to 13	13 to 14	14 to 15	15 to 16	16 to 17	17 to 18	18 to 19	19 to 20	20 to 21	21 to 22	22 to 23	23 to 24
	12	12	12	12	18	18	18	18	18	18	12	12	12	12	12	12	18	18	18	18	18	12	12	12

Shortcut to fill hours

From: To: Value: Apply

☐ tick if it is for holiday

Record: 2905 of 4054 No Filter Search

Living room

Occupancy

Activity Database

Activity Daily Schedule Weekly Schedule Annual Schedule General

Daily Schedules

Object selector: **Dwell_DomLounge_Occ_Wkdy**

General

Name: **Dwell_DomLounge_Occ_Wkdy** Description:

Type: FRACTION

Category: OCCUPANCY

Source: BRE estimates

Hours:

0 to 1	0	6 to 7	0	12 to 13	0	18 to 19	1
1 to 2	0	7 to 8	0	13 to 14	0	19 to 20	1
2 to 3	0	8 to 9	0	14 to 15	0	20 to 21	1
3 to 4	0	9 to 10	0	15 to 16	0	21 to 22	1
4 to 5	0	10 to 11	0	16 to 17	0.5	22 to 23	0.6667
5 to 6	0	11 to 12	0	17 to 18	0.5	23 to 24	0

Shortcut to fill hours:

From: To: Value: Apply

☐ tick if it is for holiday

Record: 236 of 4054 No Filter Search

Lighting – 4.1 W/m²

Activity Database

Activity Daily Schedule Weekly Schedule Annual Schedule General

Daily Schedules

Object selector: **Dwell_DomLounge_Light_Wkdy**

General

Name: **Dwell_DomLounge_Light_Wkdy** Description:

Type: FRACTION

Category: LIGHTING

Source: BRE estimates

Hours:

0 to 1	0	6 to 7	0	12 to 13	0	18 to 19	1
1 to 2	0	7 to 8	0	13 to 14	0	19 to 20	1
2 to 3	0	8 to 9	0	14 to 15	0	20 to 21	1
3 to 4	0	9 to 10	0	15 to 16	0	21 to 22	1
4 to 5	0	10 to 11	0	16 to 17	1	22 to 23	1
5 to 6	0	11 to 12	0	17 to 18	1	23 to 24	0

Shortcut to fill hours:

From: To: Value: Apply

☐ tick if it is for holiday

Record: 1051 of 4054 No Filter Search

Equipment – 3.9 W/m²

Activity Database

Activity Daily Schedule Weekly Schedule Annual Schedule General

Daily Schedules

Object selector: **Dwell_DomLounge_Equip_Wkdy**

General

Name: **Dwell_DomLounge_Equip_Wkdy** Description:

Type: FRACTION

Category: EQUIPMENT

Source: BRE estimates

Hours:

0 to 1	0.0641	6 to 7	0.0641	12 to 13	0.0641	18 to 19	1
1 to 2	0.0641	7 to 8	0.0641	13 to 14	0.0641	19 to 20	1
2 to 3	0.0641	8 to 9	0.0641	14 to 15	0.0641	20 to 21	1
3 to 4	0.0641	9 to 10	0.0641	15 to 16	0.0641	21 to 22	1
4 to 5	0.0641	10 to 11	0.0641	16 to 17	0.5321	22 to 23	0.6880
5 to 6	0.0641	11 to 12	0.0641	17 to 18	0.53206	23 to 24	0.0641

Shortcut to fill hours:

From: To: Value: Apply

☐ tick if it is for holiday

Record: 1859 of 4054 No Filter Search

Activity Database

Activity Daily Schedule Weekly Schedule Annual Schedule General

Daily Schedules

Object selector: **Dwell_DomLounge_Equip_Wknd**

General

Name: **Dwell_DomLounge_Equip_Wknd** Description:

Type: FRACTION

Category: EQUIPMENT

Source: BRE estimates

Hours:

0 to 1	0.0641	6 to 7	0.0641	12 to 13	1	18 to 19	1
1 to 2	0.0641	7 to 8	1	13 to 14	1	19 to 20	1
2 to 3	0.0641	8 to 9	1	14 to 15	1	20 to 21	1
3 to 4	0.0641	9 to 10	1	15 to 16	1	21 to 22	1
4 to 5	0.0641	10 to 11	1	16 to 17	1	22 to 23	1
5 to 6	0.0641	11 to 12	1	17 to 18	1	23 to 24	0.3449

Shortcut to fill hours:

From: To: Value: Apply

☐ tick if it is for holiday

Record: 1860 of 4054 No Filter Search

Setpoint – Heating at 18°C

Activity Database

Activity Daily Schedule Weekly Schedule Annual Schedule General

Daily Schedules

Object selector **Dwell_DomLounge_Heat_Wkdy**

General

Name **Dwell_DomLounge_Heat_Wkdy** Description

Type TEMPERATURE

Category TEMPERATURE SET POINTS

Source BRE estimates

Hours

0 to 1	12	6 to 7	12	12 to 13	12	18 to 19	21
1 to 2	12	7 to 8	12	13 to 14	12	19 to 20	21
2 to 3	12	8 to 9	12	14 to 15	21	20 to 21	21
3 to 4	12	9 to 10	12	15 to 16	21	21 to 22	21
4 to 5	12	10 to 11	12	16 to 17	21	22 to 23	21
5 to 6	12	11 to 12	12	17 to 18	21	23 to 24	12

Shortcut to fill hours

From

To

Value

Apply

☐ tick if it is for holiday

Record: 2917 of 4054 No Filter Search

Communal areas / Circulation / Restrooms

Occupancy

Activity Database

Activity Daily Schedule Weekly Schedule Annual Schedule General

Daily Schedules

Object selector: **Dwell_DomCirculation_Occ_Wkdy**

General

Name: **Dwell_DomCirculation_Occ_Wkdy** Description:

Type: FRACTION

Category: OCCUPANCY

Source: BRE estimates

Hours:

0 to 1	0	6 to 7	0	12 to 13	0	18 to 19	0
1 to 2	0	7 to 8	1	13 to 14	0	19 to 20	0.2
2 to 3	0	8 to 9	1	14 to 15	0	20 to 21	0.2
3 to 4	0	9 to 10	1	15 to 16	0	21 to 22	0.2
4 to 5	0	10 to 11	0	16 to 17	0	22 to 23	0.2
5 to 6	0	11 to 12	0	17 to 18	0	23 to 24	0

Shortcut to fill hours:

From: To: Value: Apply

☐ tick if it is for holiday

Record: 14 224 of 4054 No Filter Search

Activity Database

Activity Daily Schedule Weekly Schedule Annual Schedule General

Daily Schedules

Object selector: **Dwell_DomCirculation_Occ_Wknd**

General

Name: **Dwell_DomCirculation_Occ_Wknd** Description:

Type: FRACTION

Category: OCCUPANCY

Source: BRE estimates

Hours:

0 to 1	0	6 to 7	0	12 to 13	1	18 to 19	1
1 to 2	0	7 to 8	1	13 to 14	1	19 to 20	1
2 to 3	0	8 to 9	1	14 to 15	1	20 to 21	1
3 to 4	0	9 to 10	1	15 to 16	1	21 to 22	1
4 to 5	0	10 to 11	1	16 to 17	1	22 to 23	1
5 to 6	0	11 to 12	1	17 to 18	1	23 to 24	0.3

Shortcut to fill hours:

From: To: Value: Apply

☐ tick if it is for holiday

Record: 14 225 of 4054 No Filter Search

Lighting – 2.8W/m²

Activity Database

Activity Daily Schedule Weekly Schedule Annual Schedule General

Daily Schedules

Object selector: **Dwell_DomCirculation_Light_Wkdy**

General

Name: **Dwell_DomCirculation_Light_Wkdy** Description:

Type: FRACTION

Category: LIGHTING

Source: BRE estimates

Hours:

0 to 1	0	6 to 7	0	12 to 13	0	18 to 19	0
1 to 2	0	7 to 8	1	13 to 14	0	19 to 20	1
2 to 3	0	8 to 9	1	14 to 15	0	20 to 21	1
3 to 4	0	9 to 10	1	15 to 16	0	21 to 22	1
4 to 5	0	10 to 11	0	16 to 17	0	22 to 23	1
5 to 6	0	11 to 12	0	17 to 18	0	23 to 24	0

Shortcut to fill hours:

From: To: Value: Apply

☐ tick if it is for holiday

Record: 14 1038 of 4054 No Filter Search

Activity Database

Activity Daily Schedule Weekly Schedule Annual Schedule General

Daily Schedules

Object selector: **Dwell_DomCirculation_Light_Wknd**

General

Name: **Dwell_DomCirculation_Light_Wknd** Description:

Type: FRACTION

Category: LIGHTING

Source: BRE estimates

Hours:

0 to 1	0	6 to 7	0	12 to 13	1	18 to 19	1
1 to 2	0	7 to 8	1	13 to 14	1	19 to 20	1
2 to 3	0	8 to 9	1	14 to 15	1	20 to 21	1
3 to 4	0	9 to 10	1	15 to 16	1	21 to 22	1
4 to 5	0	10 to 11	1	16 to 17	1	22 to 23	1
5 to 6	0	11 to 12	1	17 to 18	1	23 to 24	1

Shortcut to fill hours:

From: To: Value: Apply

☐ tick if it is for holiday

Record: 14 1039 of 4054 No Filter Search

Equipment – 2.16 W/m²

Activity Database

Activity Daily Schedule Weekly Schedule Annual Schedule General

Daily Schedules

Object selector: **Dwell_DomCirculation_Equip_Wkdy**

General

Name: **Dwell_DomCirculation_Equip_Wkdy** Description:

Type: FRACTION

Category: EQUIPMENT

Source: BRE estimates

Hours	0 to 1	1 to 2	2 to 3	3 to 4	4 to 5	5 to 6	6 to 7	7 to 8	8 to 9	9 to 10	10 to 11	11 to 12	12 to 13	13 to 14	14 to 15	15 to 16	16 to 17	17 to 18	18 to 19	19 to 20	20 to 21	21 to 22	22 to 23	23 to 24
	0.0637	0.0637	0.0637	0.0637	0.0637	0.0637	0.0637	0.5318	0.5318	0.5318	0.0637	0.0637	0.0637	0.0637	0.0637	0.0637	0.0637	0.0637	0.5318	0.7659	1	1	0.7659	0.2978

Shortcut to fill hours

From: To: Value:

Apply

☐ tick if it is for holiday

Record: 1846 of 4054 No Filter Search

Activity Database

Activity Daily Schedule Weekly Schedule Annual Schedule General

Daily Schedules

Object selector: **Dwell_DomCirculation_Equip_Wknd**

General

Name: **Dwell_DomCirculation_Equip_Wknd** Description:

Type: FRACTION

Category: EQUIPMENT

Source: BRE estimates

Hours	0 to 1	1 to 2	2 to 3	3 to 4	4 to 5	5 to 6	6 to 7	7 to 8	8 to 9	9 to 10	10 to 11	11 to 12	12 to 13	13 to 14	14 to 15	15 to 16	16 to 17	17 to 18	18 to 19	19 to 20	20 to 21	21 to 22	22 to 23	23 to 24
	0.0637	0.0637	0.0637	0.0637	0.0637	0.0637	0.0637	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0.3446

Shortcut to fill hours

From: To: Value:

Apply

☐ tick if it is for holiday

Record: 1847 of 4054 No Filter Search

Setpoint – Heating at 18°C

Activity Database

Activity Daily Schedule Weekly Schedule Annual Schedule General

Daily Schedules

Object selector: **Dwell_DomCirculation_Heat_Wkdy**

General

Name: **Dwell_DomCirculation_Heat_Wkdy** Description:

Type: TEMPERATURE

Category: TEMPERATURE SET POINTS

Source: BRE estimates

Hours	0 to 1	1 to 2	2 to 3	3 to 4	4 to 5	5 to 6	6 to 7	7 to 8	8 to 9	9 to 10	10 to 11	11 to 12	12 to 13	13 to 14	14 to 15	15 to 16	16 to 17	17 to 18	18 to 19	19 to 20	20 to 21	21 to 22	22 to 23	23 to 24
	12	12	12	12	12	18	18	18	18	18	12	12	12	12	12	12	12	18	18	18	18	18	12	

Shortcut to fill hours

From: To: Value:

Apply

☐ tick if it is for holiday

Record: 2892 of 4054 No Filter Search

Activity Database

Activity Daily Schedule Weekly Schedule Annual Schedule General

Daily Schedules

Object selector: **Dwell_DomCirculation_Heat_Wkdy**

General

Name: **Dwell_DomCirculation_Heat_Wkdy** Description:

Type: TEMPERATURE

Category: TEMPERATURE SET POINTS

Source: BRE estimates

Hours	0 to 1	1 to 2	2 to 3	3 to 4	4 to 5	5 to 6	6 to 7	7 to 8	8 to 9	9 to 10	10 to 11	11 to 12	12 to 13	13 to 14	14 to 15	15 to 16	16 to 17	17 to 18	18 to 19	19 to 20	20 to 21	21 to 22	22 to 23	23 to 24
	12	12	12	12	12	18	18	18	18	18	12	12	12	12	12	12	12	18	18	18	18	18	12	

Shortcut to fill hours

From: To: Value:

Apply

☐ tick if it is for holiday

Record: 2892 of 4054 No Filter Search

Appendix F – LCCF and LCC Assumptions

Energy cost increase, on top of inflation	10% every 5 years (BSRIA, 2016)
Discount rate	3% (BSRIA, 2016)
Gas emission rates	0.216 kgCO ₂ /kWh (NCM, 2016)
Gas cost (including assumed annual standing charge and VAT)	0.045 £/kWh (UK Power, 2017)
Electricity emission rates	0.519 kgCO ₂ /kWh (NCM, 2016)
Electricity cost (including assumed annual standing charge and VAT)	0.16 £/kWh (UK Power, 2017)
Assumed boiler life span	15 years
Boiler unadjusted cost	£2,000
Initial boiler efficiency	93%
Annual reduction in boiler efficiency	1%